technologies

MDPI

Article

Validation of Different Filters for Center of Pressure Measurements by a Cross-Section Study

Jan Jens Koltermann [1,2,*], Martin Gerber [3], Heidrun Beck [1] and Michael Beck [2]

[1] University Center for Orthopedic and Trauma Surgery, Faculty of Medicine Carl Gustav Carus, Technische Universität Dresden, 01307 Dresden, Germany; Heidrun.Beck@uniklinikum-dresden.de
[2] Institute of Electrical Systems and Energy Logistics, Faculty of Mechanical Engineering, Electrical and Energy Systems, Brandenburg University of Technology Cottbus-Senftenberg, 01968 Senftenberg, Germany; Michael.Beck@b-tu.de
[3] SLG Prüf- und Zertifizierungs GmbH, Medical Devices and Laser Safety, 09232 Hartmannsdorf, Germany; M.Gerber@slg.de.com
* Correspondence: Jan1.koltermann@leag.de; Tel.: +49-354-2874-374

Received: 26 July 2019; Accepted: 17 September 2019; Published: 20 September 2019

Abstract: The measurement of the center of pressure (CoP) is one of the most frequently used quantitative methods for quantifying postural performance. Due to the complexity and the high biological variability of the postural control loop, a large number of different methods and parameters have been established to describe the CoP process. Furthermore, the methodological conditions such as the foot position, visual condition, sampling duration, and the data processing also have a relevant influence on the measurement results. In addition, there are various methods for recording the pressure curve, which differ in particular with regard to the filters used, the frequencies, and measurement times. The aim of the present study was the methodical comparison between different digital filters, measurement frequencies and times, and their effects on the CoP process based on a healthy reference group. The data acquisition was done with LabVIEW and the data storage was organized in a subject oriented data structure. Based on the presented results it could be seen that with a different dominant frequency in the spectrum of the group of test persons, certain filter types are required for the processing of CoP data. In the sampling range from 300 Hz to 1 kHz in the bipedal stand and 600 Hz to 1 kHz in the monopedal stand, the choice of measurement frequency had no influence on the filter result.

Keywords: CoP; force plate; AMTI; Kistler; center of pressure; postural control; balance; filter; Butterworth; sampling duration effect

1. Introduction

Clinical research is increasingly based, depending on the research question, on the collection of quantitative measurement variables. Many of these parameters in the medical context appear to be time-constant, but have a time-dependent component when analyzed in detail. This temporal dependence leads to the fact that the result or the meaningfulness of the analysis of a measurement series can differ from each other with increasing measurement time. Consequently, the measurement period in which these signals are observed must always be correctly determined in order to obtain the optimum measurement result with the highest significance.

This dependence on the measurement time can be proven for a large number of measurement methods such as the measurement of stability using the center of pressure (CoP) [1]. The quantification of the CoP trajectory by means of a force plate is an established procedure in posturography, and is carried out by means of various parameters and methods, which will be presented and analyzed in the context of this study.

For example, the recording duration and the frequency with which the signals are sampled have a significant influence on the evaluation and the expected result [1,2]. The sampling frequency, in combination with the duration of the data recording, generates the data volume, which is used for evaluation. The investigations of Carpenter et al. (2001) [2] and van der Kooij (2011) [1] showed that these two essential measurement conditions had a significant influence on the overall result of a posturographic measurement.

In previous studies, there has been no uniform standard about the measuring time of the CoP, and the time span ranges from 10 s [3] up to 32 min [4]. In clinical applications, however, measurement times in the range of 10 s to 30 s are typical for analyzing the postural competence of patients. It is often argued that the patient cohort to be investigated is not able to maintain a predetermined standing position for longer, due to its limited postural capacity. Furthermore, it is assumed that fatigue effects that occur with increasing measurement time could have a negative influence on the measurement result and possibly superimpose the characteristics to be investigated. Regardless of this, the time efficiency of study setups—also against the background of a possible implementation into clinical routine—is a decisive criterion for keeping the measurement period as short as possible. The question of the "optimal" measuring time is therefore often raised.

A further criterion, which often distinguishes the studies from each other, is the choice of the stand on the force plate. The "classic" forms are the one-legged stand and the two-legged stand, whereby these two forms are further subdivided depending on other parameters (e.g., stand width, knee flexion angle, . . .). These are extended by the visual conditions (i.e., the stand is carried out with open eyes (EO) or with closed eyes (EC)). In the scientific discourse, there is also no uniform opinion regarding these conditions. Based on these findings, this study intends to make a scientific contribution to the standardization of future studies. Based on a reference group of healthy volunteers in a cross-section of society, three core parameters were examined based on the measurement results of the CoP trajectory:

- The influence of the sampling duration effect,
- the influence of the sampling frequency, and
- the influence of digital filters.

2. Influence of Measurement Time and Frequency

The influence of the two elementary measurement parameters, the measurement time and frequency, have already been the subject of several scientific investigations, therefore first partial results are available. Carpenter et al. investigated how the selected measurement period affected the statistical results of the two-leg stand. In their study, 49 subjects were measured for 120 s. For the evaluation, the complete signal curve of 120 s was divided into different time intervals starting from the start of the measurement (t0). Subsequent analysis was performed for the defined intervals of 15 s, 30 s, 60 s, and 120 s. The results showed that the effective value (RMS) increased with increasing measurement time and the mean power frequency (MPF) decreased. Furthermore, it was proven that the reliability was significantly higher with increasing measuring time [2]. The investigations by van der Kooij (2011), on the other hand, only showed a significant change in the amplitude of the MPF after 240 s [1].

Le Clair's study examined the relationship between reliability and measurement time in a two-legged stand. The basis of this study was the measured area of the CoP at 10, 20, 30, 45, and 60 s. The authors were able to prove that the reliability was lowest at 10 s, but increased with increasing measurement time (the areas of the CoP track differed significantly from each other) [5].

Based on these findings, it can be assumed that the results of the CoP measurements become more stable with increasing measurement time and are subject to less fluctuation [6]. The investigations of Vieira et al. also arrived at a similar conclusion [7]. In line with this, van der Kooij et al. (2011) showed that with a shorter measurement time, the results of the frequency-dependent parameters are larger. However, a longer measuring time cannot be substituted by merging several short intervals [1]. Durate and Zatsiorsky showed in 2001 that a "long-range" correlation with signals of 10 s and 10 min was possible. The two methods using "detrended fluctuation analysis" and "power spectral analysis" showed similar results [8].

From the study results presented, it becomes clear that the first statistically significant results can be expected after a measurement time of 30 s. The measurement frequency has another decisive influence on the results of the measurement. In 2003, Raymakers et al. were able to demonstrate in a study that there was a significant difference between the data recorded at 10 Hz and the data recorded at 50 Hz [9]. For the selection of a suitable measuring frequency, the Nyquist criterion must be observed [10]. This means that the measurement frequency has to be more than twice as large as the frequency to be measured (in this case postural fluctuation). From a technical point of view, however, there is nothing to prevent working with higher sampling times in the range of more than 100 Hz. Potential noise, which is therefore increasingly measured, can be eliminated by selecting a suitable filter, for example, a low-pass filter with a cut-off frequency of 12 Hz [10].

A primary cause for these, partly clear differences in the results, is the human state. This is characterized by a high biological variability, so that the postural fluctuations in the upright position are subject to a spontaneous and anticyclical change in amplitude and direction. This means that the upright stand consists of different fluctuation frequencies and is superimposed. The frequency range of 0.1–0.2 Hz has the largest occurrence in the spectrum of the upright state (see Figure 1). These fluctuation frequencies or their relative share have an influence on the measurement of the CoP or form the basis of this analytical method.

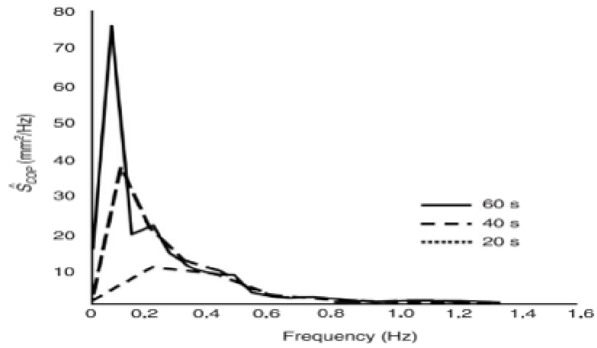

Figure 1. Frequency spectrum of a CoP signal [7].

Figure 2 exemplarily compares different frequencies of an ideal oscillation in the course of time up to 30 s. This illustration shows that with an assumed measurement time of 30 s for signal components with 0.1 Hz, only three periods can be recorded. Lower signal frequencies (e.g., 0.01 Hz and 0.033 Hz) are only detected once or not completely. If the majority of a human fluctuation of 0.1 Hz is assumed as the lower limit to be recorded, it should be possible to record this at least five times for a meaningful mean value. This corresponds to a measurement time of ≥60 s. This influence is illustrated by the representation of the frequency components in Figure 1.

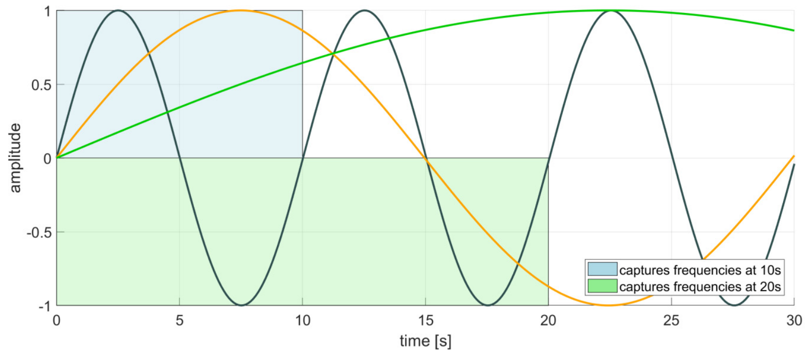

Figure 2. Representation of the temporal course of oscillations with different frequencies (0.1 Hz green; 0.01 Hz orange; 0.033 Hz black).

Both van der Kooij and Carpenter recommend measuring the CoP with 60 s or longer. Thus, a stable standard deviation (variability of the fluctuation) can be achieved [1,2], which in turn positively influences the reliability of the results [6]. When recording the CoP in the "extended position", all motion parts of the body sway can be recorded and characterized. Thus, the influence of transient effects in the CoP signal, which occur mainly in the first 20 s, can be compensated [11]. In addition, longer measurement times include a greater number of extreme values with large amplitudes [1]. The extension of the measurement time is limited by the consideration that the risk of the occurrence of fatigue effects increases with increasing time or that this requirement in particular cannot be met by restricted test persons (patients).

It is assumed that the knowledge gained for the two-leg stand can be applied analogously to the monopedal stand. This is confirmed by the examination of studies which deal with the one-leg stand. Muehlbauer and colleagues showed in a study with 39 volunteers that with increasing measuring time, the CoP results of the one-leg stand were more reproducible (intra- and intersession reliability). This applied to the "classic" CoP parameters such as area and speed. There was no quality grading between male and female subjects. The analysis of the gender groups produced excellent results in each case [12]. In 2013, Pierreira et al. investigated the differences between 11 young (average age 20 years) and 12 older adults (average age 68 years). For the analysis of the CoP, the parameter of the area in the one-legged stand was used and evaluated for the time intervals of 5, 10, 15, and 30 s, respectively. Although it could be shown that the results for the age groups were for the first time selective from 10 s onwards, the CoP area had not yet reached an almost stationary state even after 30 s. The results were not as clear as they had been before. The authors were able to demonstrate that their results became more meaningful over time [13]. In 1999, Riemann investigated the extent to which the measurement results differed between the various stand positions (one-legged vs. two-legged stand). It was shown that after 20 s, no variance could be observed in the measurement in the two-legged position and therefore no correlation with other parameters could be determined. However, this could be done for the one-leg stand with very good results [14]. In a later investigation, Riemann was able to prove that different visual conditions (eyes open/closed) achieved a very good correlation after 20 s in the stand [15].

3. Materials and Methods

In this study, 218 healthy volunteers were recruited between the ages of 18 and 90, without any restrictions of the motoric neurological or vestibular system. The study clientele consisted of 116 male and 105 female volunteers. The anthropometric data of the patients are summarized in Table 1.

The absolute age distribution of the test persons is shown in Figure 3, where the relatively small proportion of subjects over the age of 60 is due to the inclusion criteria, which required complete freedom from all motor impairments.

The CoP was measured using two Kistler 9260AA force plates, which were operated at a sampling rate of 1 kHz. As A/D converter modules by Meilhaus of the type Redlab 1608 with a sampling rate of 16 Bit were used on the software side, the raw data were recorded and the COP or COP progression was calculated using LabVIEW 2014 from National Instruments (Austin, TX, USA). The data acquisition was programmed in a way that each subject was measured under the same conditions in a defined sequence.

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

	Total Group	Male (52%)	Female (48%)
Age (J.)	39.9 ± 17.5	40.4 ± 16.6	40.54 ± 17.66
Weight (kg)	75.8 ± 15.6	83.9 ± 13.7	66.13 ± 11.93
Size (cm)	171.5 ± 25.8	180.9 ± 7.7	160.30 ± 34.21
BMI (kg/m^2)		25.6 ± 3.8	24.2 ± 4.5
Shoe size (EU)	42.8 ± 2.7	42.5 ± 5.5	38.9 ± 1.5

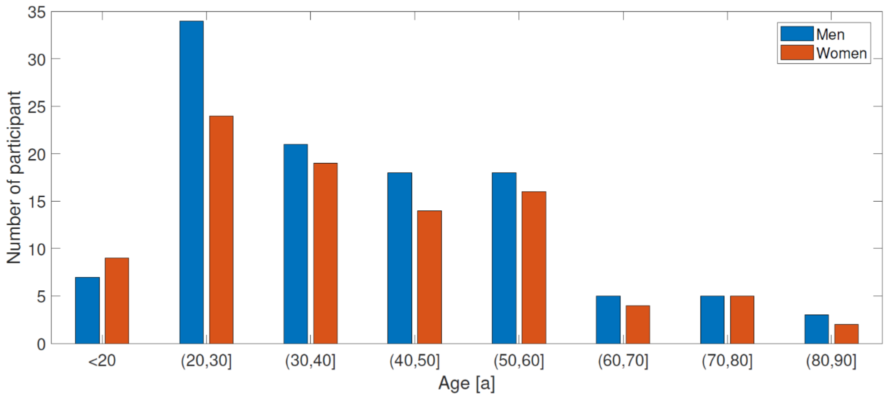

Figure 3. Age distribution of the test persons.

3.1. Method

The study was carried out in the form of a cross-sectional study. The test persons were measured in standardized order and under constant conditions in four different conditions:

- monopedal left, eyes open
- bipedal, eyes open
- monopedal right, eyes open
- bipedal, eyes closed

There was a break of 5 min between each condition. The standardization of the sequence was necessary to detect and evaluate possible fatigue effects in the subsequent analysis. The recording time was limited to 120 s per measurement. The limitation was chosen based on the results from van der Kooij and Collins as the influence of fatigue is considered small. [1,16] If signs of increasing instability or loss of equilibrium appeared before this time had elapsed, the measurement was stopped and the data recorded up to that point were saved. To secure the subject in the one-leg stand (especially with older test participants), a volunteer was located at the side outside the field of vision of the test subject in order to support them.

To standardize the standing position, the standing surface of the force plate was provided with optical markings that specified the positioning of the foot or feet, depending on the condition of the measurement. In addition, an optical mark was attached at a distance of 3 m from the measuring station, which the test person was supposed to fix with their eyes during measurement conditions 1 to 3.

3.2. Analysis

The software-supported analysis of the measurement recordings was carried out using LabVIEW from National Instruments (Austin, TX, USA). The position of the CoP or the course of the CoP over the measuring time was determined from the raw data of the determined force distributions (force plate). As a central parameter of the CoP trajectory, the travelled distance of the CoP was determined (CoP length) and used for further analysis. The results were presented as mean values of the overall cohort.

For down sampling, an algorithm was designed that was applied to the raw values. This algorithm provided for a gradual reduction of the sampling frequency from 1 kHz to the lowest frequency of 2 Hz. The raw values were filtered with the filters integrated in LabVIEW. The second and seventh order Butterworth filters and the seventh order Bessel filters were applied to the raw data.

4. Results

4.1. Influence of the Sampling Duration Effect

The sampling duration effect describes the influence of the duration of a measurement on the result. The length of the CoP track, resulting from the fluctuation of the respondent over time, is characterized by a progressive progression. Figure 4 shows the time development of the bipedal state in the time range from 0 to 120 s (EO/EC). All test persons in the bipedal state were able to fully complete the maximum standing time of 120 s.

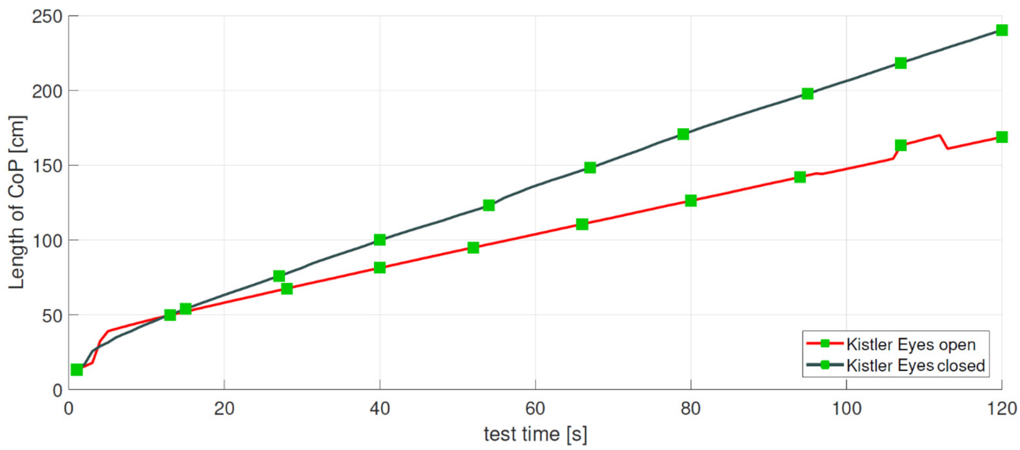

Figure 4. Absolute CoP length curve for bipedal stand over the measurement time, with open eyes (red) and closed eyes (black).

The CoP track curves shown in Figure 4 differed with increasing measurement time depending on the visual condition. Within the first 5 s of the measurement, both courses showed an unstable phase of "transient oscillation", but with increasing time, these changed into an almost linear increase (eyes open: $r = 0.996$; eyes closed: $r = 0.985$). It could be seen that with increasing measuring time, the absolute distance of the CoP fluctuations increased.

As expected, the extent of fluctuations without visual control (EC) was significantly higher than with open eyes (EO). With the exception of the "transient" phase, this effect was evident over the entire course of the measurement, so that with increasing measurement time, the difference between measurement conditions continued to increase and reached its maximum at 120 s.

An analogous, albeit not so clearly pronounced, behavior was also detectable for the monopedal state. The respective courses are compared in Figure 5 for the absolute CoP length in each case for the right and left standing leg.

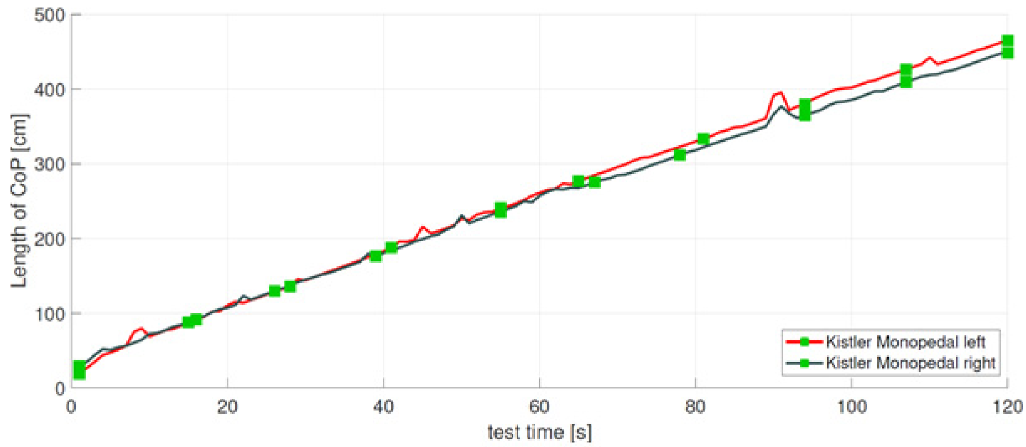

Figure 5. Absolute CoP length curve for monopedal stand over the measurement time, with left (red) and right leg (black).

Similar to the bipedal stand, a "transient" phase is also recognizable for the one-leg stand, which changes into a stable ascent after approximately 5 s. Irrespective of the preferred side, this increase is largely linear, although not over the entire course.

In the monopedal condition, 125 subjects on the left leg and 117 subjects on the right leg were able to complete the maximum standing time of 120 s in full. The course of the CoP length showed a correlation of r = 0.99 on average. A comparably stronger linear correlation could also be determined for the test persons who were not able to maintain the equilibrium for the full 120 s (r = 0.92).

4.2. Influence of Sampling Frequency

In addition to the measurement time, the influence of the measurement frequency was also quantified in this study. The results of this analysis are shown in the following figures (Figures 6 and 7, Absolute CoP length) for the bipedal and monopedal states. The results were filtered with a second order Butterworth filter with a cut-off frequency of 12 Hz.

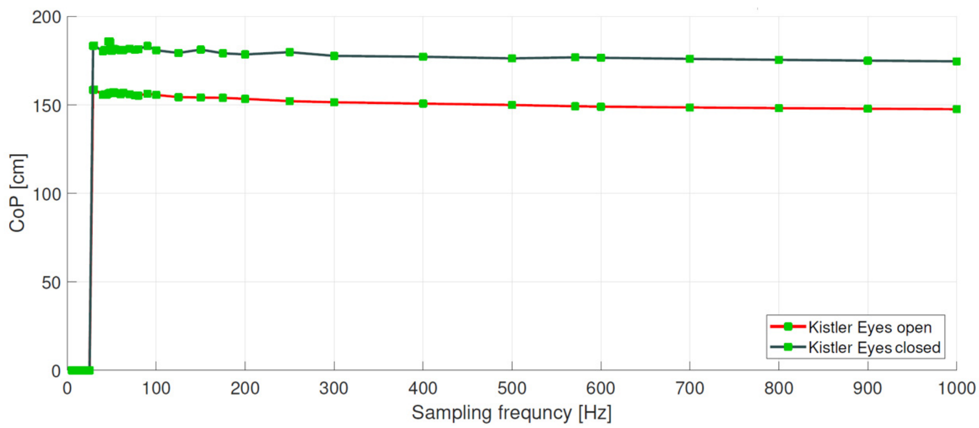

Figure 6. Absolute CoP length curve as a function of the sampling frequency used in the bipedal state, with open (EO) and closed eyes (EC), respectively.

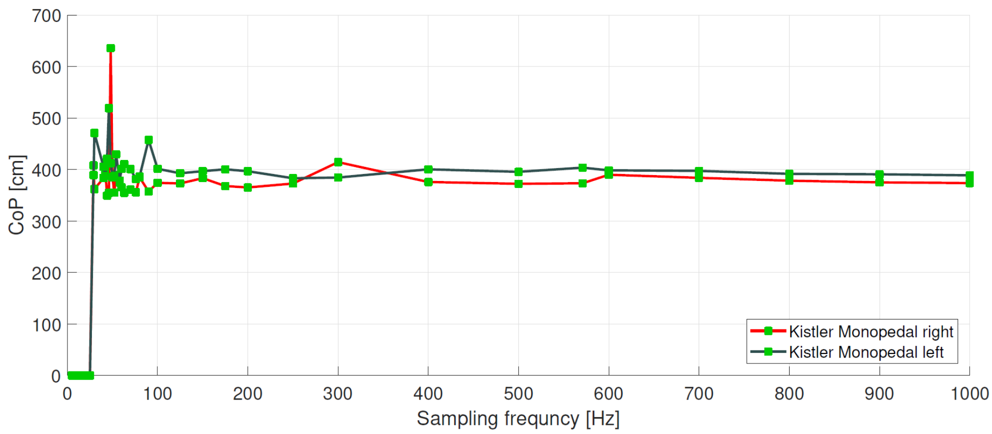

Figure 7. Absolute CoP length curve as a function of the sampling frequency used in the monopedal stand, for the left and right leg.

Due to the filter used, the CoP curves showed a sudden increase at 24 Hz. In the range below 24 Hz, the filtered signals did not provide a useful result, since the Nyquist criterion was below the technical limit for the filters (twice cut off frequency = 24 Hz) [16]. In the range above 24 Hz, usable results could be calculated that explain the sudden increase (see Figures 6 and 7, Absolute CoP length).

The CoP curves of the bipedal state given in Figure 6 show that the measured values become increasingly "stable" as the sampling frequency increases. From a measuring frequency of approximately 300 Hz, an approximately linear curve could be observed for the bipedal state (orange dividing line), whereby the absolute length of the CoP's decreased slightly with increasing frequency. The visual condition seemed to only cause a vertical shift, and significant differences in the course were not evident ($p > 0.05$). On the other hand, there were clear differences between the bipedal and monopedal stand.

The Figure 7, absolute CoP length, shows the length of the CoP track for the monopedal stand as a function of the sampling frequency used. Analogous to the bipedal state, a sudden increase at 24 Hz was also observed with this test condition, which was caused by the filter used or its cut-off frequency. In the further course above 24 Hz, however, a stochastic distribution of the results was observed, especially in the range up to 100 Hz. Only at a sampling frequency of 600 Hz was a stable state with a linear relationship $r \geq 0.97$ (orange dividing line) achieved. Significant differences between the standing leg side were not detectable for the present cohort.

4.3. Influence of Digital Filters

The post-processing of raw data with a filter is essential for CoP trajectory. The choice of a suitable filter depends on the question, but a uniform standard does not exist yet.

From previous studies by Koltermann et al., it is already known that using a technical pendulum and the Butterworth and Bessel filters yielded results in the expected range at different orders with cut-off frequencies between 13 and 15 Hz [16]. For this reason, the range between 13 and 15 Hz was assumed to be the confidence range for this study. Based on these findings, the first step was to evaluate the cut-off frequencies for the entire cohort using a second-order Butterworth filter. The results are shown in Figure 8. In the bipedal state, the curves for both visual conditions (EO/EC) showed a linear range between a cut-off frequency of 10 to 20 Hz.

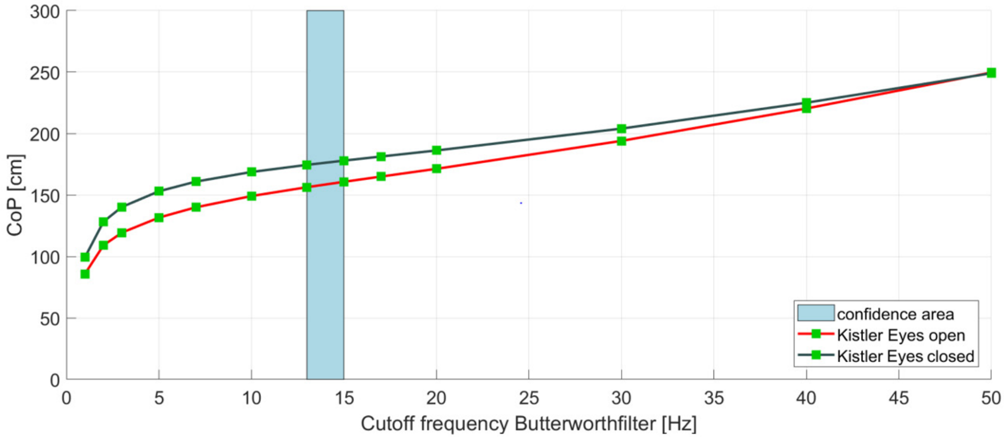

Figure 8. Result of the variation of different filter frequencies in the bipedal state for the measurement conditions of eyes open (red) and eyes closed (black).

The filters were applied analogously to the monopedal stand, in each case for the right (orange) and left leg (blue, see Figure 9). The linear course of the CoP track was not set for the stand condition per page until 13 Hz. This can be interpreted as an indication of the presence of a larger frequency width in the spectrum. Additionally, side-dependent discrepancy only occurred from 13 Hz, although this was not very pronounced and remained almost constant over the variation of the cut-off frequencies up to 50 Hz.

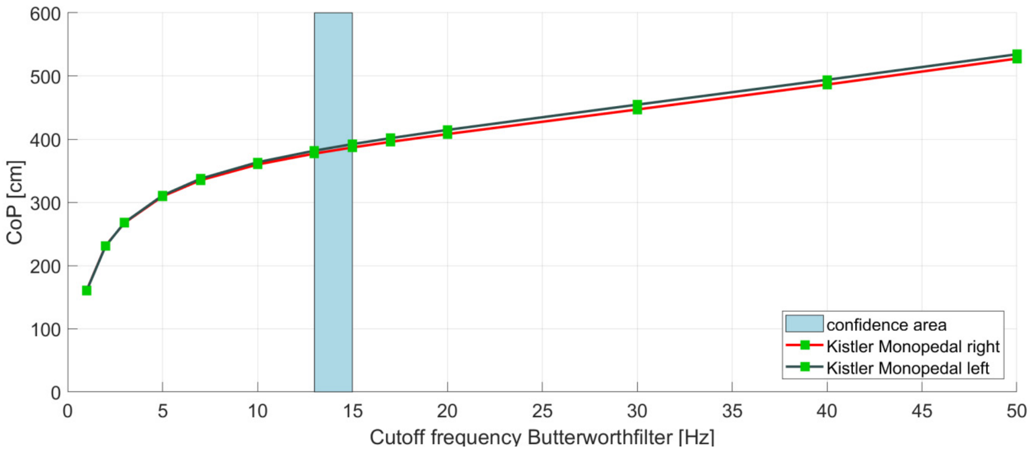

Figure 9. Result of the variation of different filter frequencies for the measurement conditions of monopedal left (black) and monopedal right (red).

5. Discussion

CoP trajectory is one of the most commonly used quantitative methods for determining postural performance. Like most quantitative measurement methods, this method is subject to time-dependent influence due to the specific parameters of the respective survey. In particular, the selection of the measurement frequency and time can in the worst case negatively influence the measurement of the actual target quantity, the course of the CoP, thus leading to wrong conclusions in the interpretation. So far, however, there is no uniform standard with regard to data collection, and recommendations regarding the optimization of data recording are inadequate. This circumstance makes it more difficult to compare different studies with each other.

For this reason, the present study examined the influence of three different parameters on the CoP survey:

- the influence of the sampling duration effect,
- the influence of the sampling frequency, and
- the influence of digital filters.

The study was carried out on a reference group of healthy volunteers who were recruited on the basis of a cross-section of society. The CoP curves of the respective test persons were determined on the basis of different measurement conditions (EO/EC) of the mono- and bipedal state and subsequently evaluated and compared using different measurement times and frequencies as well as several digital filters.

5.1. Sampling Duration Effect

The sampling duration effect describes the behavior of measurement results as a function of the measurement time used. When recording time-independent measured variables, the length of the measurement time has no influence on the consecutive result. In contrast, there are time-dependent variables such as the CoP trajectory, which are dependent on the selected measurement time and are thus inevitably influenced. Therefore, the sampling duration effect describes the relationship between measurement time and change in the result and should be taken into account when evaluating or comparing different study results.

To quantify this effect, the subjects in this study were measured for 120 s in different positions. In the bipedal state, no significant fatigue condition was evident over the entire measurement period and thus does not appear to be a limiting factor in this constellation. All test persons were able to successfully complete the bipedal motor task of 2 min. After a “transient” phase of approximately 5 s, an almost linear course was detectable. In this respect, to improve the reliability, it seems advisable not to consider the 5 s of a measurement in the later evaluation, since there is a predominantly unstable phase in this time range. Digital filters are usually not able to compensate for this unstable phase, since the corresponding filters cannot create any meaningful compensation due to their “charging time” [10]. In a time range over 30 s ($30 < t \leq 120$), there seems to be a predominantly linear correlation ($r = 0.97$), so the results can be interpolated under certain conditions. This could be an important factor in the comparability of different studies.

The results are in line with previous studies. In 2012, Schubert et al. investigated various linear and non-linear parameters with respect to their dependence on the selected measurement time. For their investigation, they used a set consisting of 24 different CoP parameters, which in turn were assigned to different groups. The parameters were divided into time-based, one-dimensional (e.g., path in A/P & M/L) and two-dimensional parameters (e.g., CoP area) as well as frequency-based parameters (e.g., average frequency in Fourier analysis). The parameters were evaluated in a bipedal state for different measurement times of 30 s, 60 s, and 300 s in length. It could be seen that a longer measurement time produces more reliable results and is therefore preferable. Based on the findings of this study, they recommended using a measurement period of at least 120 s. If the test setup allows, if possible, even a measurement period of 300 s should be chosen [17].

The study carried out here also showed that linearity could also be transferred to the results without visual control (EC). The CoP process is also characterized by an unstable phase of less than 5 s, which later changes into a stable phase. It should be noted, however, that this increase differs from the increase with the eyes open.

5.2. Digital Filters

Digital filters are an indispensable tool in the post-processing of CoP raw signals. They enable the reduction of signal noise, which superimposes the actual measurement signal. Only by reducing the noise can the actual CoP signal be used for evaluation, so that statements about postural performance are possible.

As already mentioned, the measurement time has a significant influence on frequency-dependent parameters. In previous studies, the special influence of the measurement time on the frequency-dependent parameters has already been proven [7]. Several studies have already shown that 95% of the frequency components of the CoP's are below 1 Hz [7,17]. This finding coincides with the results of Durate and Zatsiorsky, among others. These studies showed in 1999 that in the CoP track high frequencies superimpose very low frequencies which, however, cannot be detected with short measurement times (<30 s) [8]. Consequently, the measurement time has a significant influence not only on the result per se, but also on the imageable frequencies and thus also indirectly on the design of a filter to be applied. Consequently, a digital filter for a dataset with a short measurement time must be parameterized differently than a filter for a dataset with a longer recording time.

In the present study, it could be seen analogously that 93% of all frequency parts were below 1 Hz and 97% below 5 Hz. Only by filtering with the described filter design were 95% of all frequency components below 1 Hz determined. The considerations made by Koltermann et.al on the application of filters by means of a technical pendulum and the filter-CoP-characteristics thus created can be partially transferred to the biological system (human body sway in quiet stance). In combination with the filter properties analyzed in this study, the following recommendations can be made for filtering the CoP track:

Due to its pronounced linear characteristic at low cut-off frequencies, the 2nd order Chebyshev filter is suitable for processing groups of test persons with a concentrated spectrum of low frequencies (determined cut-off frequency fs < 13 Hz). In a medium frequency range from 13 to 16 Hz, a Butterworth filter of 3rd order is suitable, due to its flat shape [16]. The Bessel 7th order filter is suitable for higher cut-off frequencies, especially for operation with cut-off frequencies above 16 Hz [16].

The question of the "right" border frequency always leads to confusion. Within the scope of this study, a method was developed to determine the minimum cut-off frequency. This is based on the analysis of the available average power components, determined by Power Density Analysis, of the frequencies occurring in the spectrum of the entire cohort, which are available over the entire spectrum. The percentage distribution ranges from 100%, corresponding to 0 Hz, to 0%, of the highest analyzable frequency. Figure 10 illustrates the frequency distribution (blue line) available for this study. In the present case, 93% of all power components in the spectrum below a frequency of 1 Hz are converted. For comparison, the height of the frequency change per Hz (Δ) was plotted in the graph (orange line). To determine the relevant fundamental frequency, the intersection point is calculated at which the change in the power components in the spectrum is less than 0.1%. In the area of this intersection it can be assumed that the system changes to a static state and the subsequent changes have no relevant influence on the measurement result.

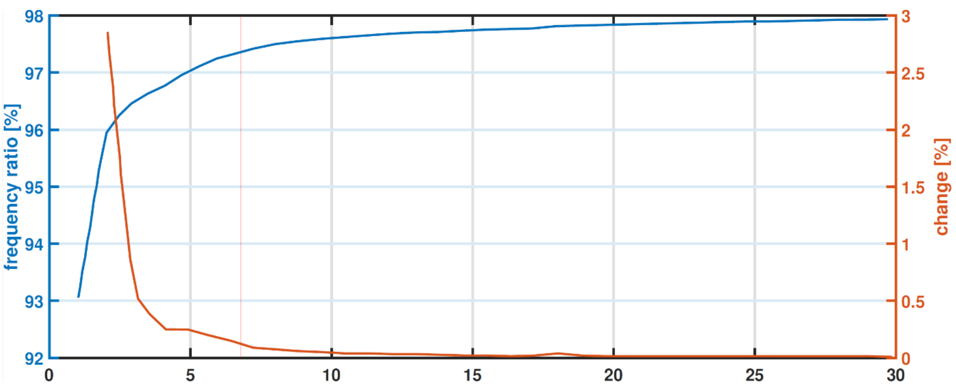

Figure 10. Representation of the mean frequency components in the entire spectrum per Hz in percent (blue) and the respective change in frequency per Hz (orange). The red line marks the limit at which the change was less than 0.1%/Hz.

On the basis of the present dataset, the relevant frequency was determined to be 6.3 Hz. The next higher integer frequency (less than 0.1% change) in this case is 7 Hz. From the Nyquist theorem, it can be deduced that the cut-off frequency should be at least twice as high as the fundamental frequency. In the present case, this corresponds to a cut-off frequency of 14 Hz.

The application of different filters with a cut-off frequency of 14 Hz is shown in Figure 11. Both the Butterworth filter of the second order (balk) and the Bessel filter of the seventh order (orange) exhibited almost identical behavior with respect to the included power components over the frequency. Below 1 Hz, both combined about 95% of the total frequency components and 99% were below a frequency of 4 Hz. This method ensures that the filter does not influence the frequencies that are important for the enhancement of the CoP signal.

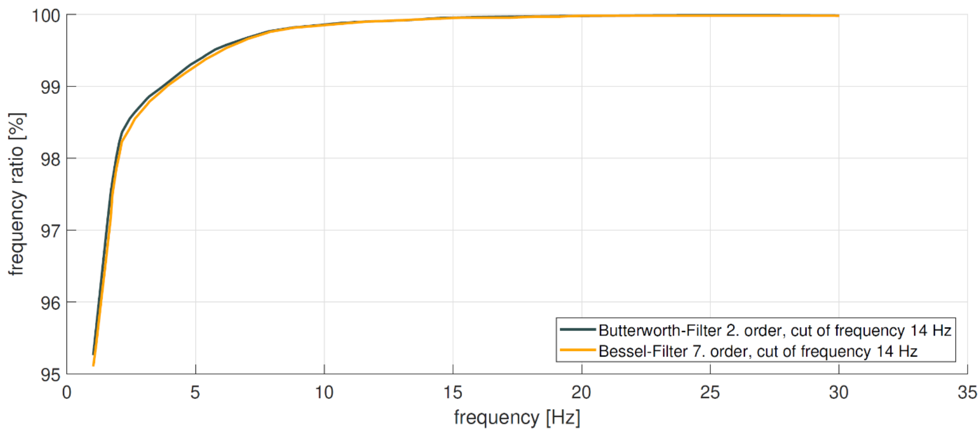

Figure 11. Representation of the mean frequency components of the entire spectrum per Hz in percent (blue) after processing the CoP track with a Butterworth second order filter (black) and a Bessel seventh order filter (orange), where the respective cut-off frequency was 14 Hz.

5.3. Sampling Frequency

In addition to the measurement time and the choice of the mathematical filter, the selected sampling rate also has an influence on the results of the CoP trajectory. In order to quantify this influence, the raw signal of the CoP track, starting at 1 kHz, was down sampled for evaluation and the results compared with each other.

Koltermann et al. showed that the results of the different filters differed only insignificantly from the raw, unfiltered CoP signal in a range from 24 Hz (Nyquist limit) to 78 Hz. In this range, the result of the CoP track was in the expected range, but did not fluctuate predictably with increasing sampling frequency. These results related to a mechanical pendulum. In contrast, in a biological system, as shown in this study, different limits seem to apply depending on the stand condition. In the bipedal state, stable values were present from 300 Hz; in the monopedal state, however, only from a sampling frequency of approximately of 600 Hz [16].

Consequently, it can be assumed that below a sampling frequency of 24 Hz in the constellation of filter parameters used here (cut-off frequency 13 Hz), the use of a filter is not effective. In the range from 24 Hz to 300 Hz/600 Hz, depending on the standing position, the use of the determined results cannot be recommended due to the high variability of the characteristic curve. When using a sampling frequency above 600 Hz, filtering is absolutely necessary to reproduce the real measurement result.

In the experiments with a mechanical pendulum, it could be seen that a stable course of the determined values was only given from a sampling rate of at least 78 Hz [16]. The results of this study show that human fluctuation in the upright position shifts this limit in favor of higher frequencies and that the unstable phase appears to be much more pronounced. In the present case, the minimum sampling frequency was 300 Hz for the bipedal stand and 600 Hz for the monopedal stand.

When considering the correlation of values between different time intervals, different results are available in the literature. Van der Kooij H (2011) could not prove a correlation between 60 and 600 s [1], but Durate and Zatsiorsky found a correlation between 60 and 600 s in their experiments [8]. In the present study, a linear course and a good correlation could be observed over the entire subject spectrum in the range of 30 to 120 s. This led to the conclusion that in these areas, the results can be scaled and so there is a possibility with the same data processing.

6. Summary

The necessity of a standardization of static posturography was demonstrated in 1981 at the Symposium of Posturography in Kyoto [18]. Since then, a large number of scientific papers have been produced dealing with this topic. However, it has not yet been possible to reach a consensus on a scientific standard.

The aim of this study was to provide possible recommendations regarding the choice of appropriate parameters for the CoP track. In particular, the focus was on the choice of a mathematical filter and the associated measurement frequency as well as to derive statements on the sampling duration effect. For the determination of a suitable cut-off frequency and thus the selection of the correct mathematical filter, a method was presented which considered the recorded properties of the entire cohort. Table 2 lists the recommendations of a suitable filter depending on the underlying sampling frequency. To this end, it must be ensured in advance that the methodology used corresponds to the required minimum scanning frequencies. The cut-off frequencies can then be determined for the preparation of the measurements and the corresponding filters or their orders can be selected. For a determined cut-off frequency below 13 Hz, the use of a second order Chebyshev filter is recommended. A third order Butterworth filter should be used for a calculated cut-off frequency in the range from 13 to 16 Hz. For the third case, a cut-off frequency greater than 16 Hz, a Bessel filter of the seventh order should be applied to the CoP signal. The results are summarized in Table 2 below as a recommendation. The choice of order is based on the results of Koltermann et al. (2018). In the experiments presented, the Bessel seventh order filter presented the best results, since the results were always in the expected range, even at higher cut-off frequencies (up to 20 Hz).

Table 2. Compilation of various use cases for filtering CoP data.

Application	Filters	Parameter	Min. Sampling Frequencies	
			Monopedal	Bipedal
$Fs < 13$	Chebyshev filter	2nd order	600 Hz	300 Hz
$13 \leq fs < 16$	Butterworth filter	3rd order	600 Hz	300 Hz
$fs \geq 16$ Hz	Bessel filter	7th order	600 Hz	300 Hz

In comparison with the results of Carpenter et al. and Le Clari, it can be concluded that measurement times of less than 30 s are unsuitable for validly recording CoP processes. In addition to validity, they were also able to demonstrate that reliability increases significantly with increasing measurement time [2,5].

Against this background and on the basis of the results of this study, it can be concluded that the measurement time for a cross-section study should not be less than 30 s, but can be interpolated in a window between 30 s and 120 s. It can be assumed that this also applies to longitudinal studies, but must be evaluated separately. This possibility provides an approach that, with the same sampling frequencies and filter parameters, different results could be obtained on the basis of different measurement times. The course of the mean CoP's in a time window over 120 s must be determined in a separate study. However, it should be considered whether measurement times of more than 120 s are recommended for test economic reasons and potential fatigue effects. Rather, the use in a time range from 30 to a maximum of 120 s seems recommendable, depending on the question and available volunteer/patient groups. The results can at least be made comparable for healthier reference subjects by interpolation.

Author Contributions: J.J.K. and M.G. conceived and designed the experiments; J.J.K. performed the experiments; J.J.K., M.G., and M.B. analyzed the data; J.J.K., H.B., and M.B. contributed reagents/materials/analysis tools; and J.J.K. and M.G. wrote the paper.

Funding: The present study was funded by the German Federal Institute of Sport Science (http://www.bisp.de). The research was realized within the project RAN Rücken (ZMVI1-080102A/11-18). Funding was received by PP. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. van der Kooij, H.; Campbell, A.D.; Carpenter, M.G. Sampling duration effects on centre of pressure descriptive measures. *Gait Posture* **2011**, *34*, 19–24. [CrossRef] [PubMed]
2. Carpenter, M.G.; Frank, J.S.; Winter, D.A.; Peysar, G.W. Sampling duration effects on centre of pressure summary measures. *Gait Posture* **2001**, *13*, 35–40. [CrossRef]
3. Vuillerme, N.; Danion, F.; Marin, L.; Boyadjian, A.; Prieur, J.M.; Weise, I.; Nougier, V. The effect of expertise in gymnastics on postural control. *Neurosci. Lett.* **2001**, *303*, 83–86. [CrossRef]
4. Kunkel, M.; Freudenthaler, N.; Steinhoff, B.J.; Baudewig, J.; Paulus, W. Spatial-frequency-related efficacy of visual stabilisation of posture. *Exp. Brain Res.* **1998**, *12*, 471–477. [CrossRef] [PubMed]
5. Le Clair, K.; Riach, C. Postural stability measures: What to measure and for how long. *Clin. Biomech.* **1996**, *11*, 176–178. [CrossRef]
6. Ruhe, A.; Fejer, R.; Walker, B. The test-retest reliability of centre of pressure measures in bipedal static task conditions-a systematic review of the literature. *Gait Posture* **2010**, *32*, 436–445. [CrossRef] [PubMed]
7. Vieira, T.M.; Oliveira, L.F.; Nadal, J. Estimation procedures affect the center of pressure frequency analysis. *Braz. J. Med. Biol. Res.* **2009**, *42*, 665–673. [CrossRef] [PubMed]
8. Durate, M.; Zatsiorsky, V.M. Long-range correlations in human standing. *Phys. Lett. A* **2001**, *283*, 124–128. [CrossRef]
9. Raymakers, J.A.; Samson, M.M.; Verhaar, H.J.J. The assessment of body sway and the choice of the stability parameter(s). *Gait Posture* **2005**, *21*, 48–58. [CrossRef] [PubMed]
10. Koltermann, J.J.; Gerber, M.; Beck, H.; Beck, M. Validation of the HUMAC Balance System in Comparison with Conventional Force Plates. *Technologies* **2017**, *5*, 44. [CrossRef]
11. Carroll, J.P.; Freedman, W. Nonstationary properties of postural sway. *J. Biomech.* **1993**, *26*, 409–416. [CrossRef]
12. Muehlbauer, T.; Roth, R.; Mueller, S.; Granacher, U. Intra an Intersession Reliability of Balance Measures During One Leg Standing in Young Adults. *J. Strength Cond. Res.* **2011**, *25*, 2228–2234. [CrossRef] [PubMed]
13. Parreira, R.B.; Boer, M.C.; Rabello, L.; Costa Vde, S.; de Oliveira, E., Jr.; da Silva, R.A., Jr. Age-related differences in center of pressure measures during one-leg stance are time dependent. *J. Appl. Biomech.* **2013**, *29*, 312–316. [CrossRef] [PubMed]
14. Riemann, B.L.; Guskiewicz, K.M.; Shields, E.W. Relationship Between Clinical and Forceplate Measures of Postural Stability. *J. Sport Rehabil.* **1999**, *8*, 71–82. [CrossRef]
15. Riemann, B.L.; Schmitz, R. The relationship between various modes of single leg postural control assessment. *Int. J. Sports Phys. Ther.* **2012**, *7*, 257–266. [PubMed]
16. Koltermann, J.J.; Gerber, M.; Beck, H.; Beck, M. Validation of Various Filters and Sampling Parameters for a COP Analysis. *Technologies* **2018**, *6*, 56. [CrossRef]
17. Schubert, P.; Kirchner, M.; Schmidtbleicher, D.; Haa, C.T. About the structure of posturography: Sampling duration, parametrization, focus of attention. *J. Biomed. Sci. Eng.* **2012**, *6*, 508–516. [CrossRef]
18. Kapteyn, T.S.; Bles, W.; Njiokiktjien, C.J.; Kodde, L.; Massen, C.H.; Mol, J.M. Standardization in platform stabilometry being a part of posturography. *Agressologie* **1983**, *24*, 321–326. [PubMed]