Journal of Sustainability Science and Management
Volume 17 Number 12, December 2022: 120-131
eISSN: 2672-7226

PRELIMINARY COMPARISON OF THREE ACCOMMODATION MICRO FLUCTUATION REPORTING APPROACHES IN OCULAR STABILITY INVESTIGATION

AZMIR AHMAD* AND CHEN AI HONG

Optometry & Visual Science Research Centre (iROViS), Faculty of Health Sciences, Universiti Teknologi MARA (UiTM) Selangor, Puncak Alam Campus, 42300 Bandar Puncak Alam, Selangor, Malaysia.

**Corresponding author: azmir5807@uitm.edu.my*
Submitted final draft: 14 September 2022 *Accepted: 30 September 2022* http://doi.org/10.46754/jssm.2022.12.011

Abstract: Accommodation of micro fluctuation has been the subject of many studies of ocular stability. Although there are three existing micro fluctuation reporting approaches encompassing the standard deviation approach, root means square approach and Fourier transform analysis, the direct comparison of these approaches is lacking. This study aims to descriptively compare the three reporting approaches using a single subject in the initial analysis. Measurement was done on the right eye using an open-field autorefractor (WAM-5500 Grand Seiko Co., Ltd., Japan) via the dynamic mode while looking at a distant target. The standard deviation (SD) approach recorded 0.1723 D accommodation micro fluctuation which was nearly identical to the root means square (RMS) approach of 0.1719 D. As for the Fourier transform (FT) approach, the variation was apparent in the low-frequency but not in the high-frequency component. Additional analysis showed the correlation coefficient between RMS and SD, between FT and SD and between FT and RMS was at 0.5776, 0.4745 and 0.4276, respectively (all P-values <0.01). In conclusion, the accommodation micro fluctuation can be aptly described through the root means square approach as it has fewer errors than the standard deviation approach and is less complicated than the Fourier transform approach.

Keywords: Accommodation micro fluctuation, standard deviation, root means square, Fourier transform.

Introduction

Ocular stability is one important indicator of eye health to ensure good quality of functional vision (Candy & Bharadwaj, 2007). An unstable focusing system can degrade the habitual retinal image quality of viewing targets that underlie spatial vision for mobility. Visual comfort can affect a human's visual experience and optimize human well-being depending on the interaction between the human and his ocular system. Any discomfort or stress on the visual system can affect visual-related activity.

A mismatch between vergence and accommodation reflexes can be detrimental (Motlagh & Geetha, 2019). Vergence and accommodation reflexes are important in generating single binocular clear vision as any impairment in the systems leads to binocular disorders (Gruning, 1985). Among the characteristics of accommodation reflex is the instability in accommodation feedback and control which is also known as accommodation micro fluctuation (Charman & Heron, 1988). Accommodation micro fluctuation has been commonly used in previous laboratory investigations of ocular stability. Accommodation micro fluctuation is defined as the variation in accommodation responses over time that continuously improves and degrades retinal image in repetition even though it is focused optimally at the retina (Campbell *et al*., 1959). Micro fluctuation is responsible for the differences between the calculated and observed optical performance of the eye which has been shown through the variations in ocular power over a short time (Leroux *et al*., 2021) with an amplitude below 1 D and a frequency up to a few Hz. There are three characteristics of accommodation micro fluctuation. The first feature is the intrinsic biological noise shown through the high-frequency component of fluctuation (Winn *et al*., 1989). It is affected by the biological arteriole pulsation which is similar to the defocus detection threshold. The second trait is the system feedback instability which extracts directional information in temporal processing, interacting with dynamic accommodation responses to the changes in target vergence (Gray *et al*., 1993). The third quality is the feedback system in maintaining steady-state accuracy, characterized by a low-frequency component in micro fluctuation that involves the negative feedback sent to the accommodation control mechanism when viewing a stationary target (van der Heijde *et al*., 1996). Both low- and high-frequency components of micro fluctuation associated with the flexibility of crystalline lens serve as an active corrective guidance and in the maintenance of dynamic accommodation response (Charman & Heron, 2015).

The reporting style of accommodation micro fluctuation is crucial to ensure that the variation in accommodation was properly illustrated. Our search of the available literature managed to compile numerous relevant articles and the outcome was in coherence with the previous review on micro fluctuation reporting approaches (Monticone & Menozzi, 2011). There are three existing reporting approaches of the accommodation micro fluctuation that encompass standard deviation of accommodation response approach, root means square of accommodation response deviation approach and power spectrum analysis through Fourier transform. Nevertheless, there were five instrumentation types involved in accommodation micro fluctuation measurements: Continuous ultrasonographic biometry, Hartmann-Shack wavefront aberrometer, infra-red optometer, infrared-sensitive video camera with low- or high-resolution pupilometer and video-based eccentric video refractometry.

Interestingly, similar instrumentation could deliver different reporting approaches. The standard deviation approach was reported in infrared-sensitive video cameras with low- or high-resolution pupilometer (Hunter *et al*., 2000), infrared optometers (Xu *et al*., 2009) and video refractometry (Langenbucher *et al*., 2003). On the other hand, the root mean square approach could be provided from ultrasonographic biometry (Schultz *et al*., 2009), Hartmann-Shack wavefront aberrometer (Plainis *et al*., 2005), infra-red optometer (Sheppard & Davies, 2010; Hynes *et al*., 2022), infrared-sensitive video camera measurement (Anderson *et al*., 2010) and video refractometry (Candy & Bharadwaj, 2007). The same happened in the Fourier transform approach which was depicted via ultrasonographic biometry (van der Heijde *et al*., 1996), Hartmann-Shack wavefront aberrometer (Gambra *et al*., 2009), infra-red optometer (Niwa & Tokoro, 1998; Li *et al*., 2022) and videokeratorefractometry (Zhu *et al*., 2006).

Therefore, this study aimed to descriptively compare the three reporting approaches using a single subject to examine the strengths and weaknesses of each reporting approach. A direct comparison was made between the three reporting approaches using a single subject to minimize subject variation. Data was used to determine which approach was more of a good fit and provided reasonable accuracy in the reporting. Additional investigation was also conducted to quantify the correlation coefficient between the three approaches among the group of subjects in reporting the accommodation micro fluctuation.

Materials and Methods

Instrumentation

This study used an infra-red optometer as its measuring technique could provide a sampling rate of nearly 5 Hz as power spectrum analysis distributed widely below 5 Hz (Charman & Heron, 1988). A binocular free-space open-field autorefractor (WAM-5500 Grand Seiko Co., Ltd., Japan) was chosen to measure the objective refractive state as it had high repeatability (Sheppard & Davies, 2010) with 75% of spherical components and 66% of cylindrical components while the accuracy of the dynamic data collected was within the lesser range than just 0.25 D optical lens steps. As opposed to the pupillometry technique, WAM-5500 allowed rapid simultaneous pupil size and refractive measurement via the supplied function of continuous dynamic mode. WCS-1 software which was provided by the supplier was used to turn on the dynamic mode of the WAM-5500 autorefractor. The measurement started once the aligning joystick was pressed, with proper eye alignment. Continuous measurement was taken automatically until the joystick was pressed again. The time of measurement and stability state was continuously recorded. They were then imported into a Microsoft Excel spreadsheet file and transformed into time-series graph.

Subject and Preliminary Data Collection Procedure

Data was taken from one myopic subject with a spherical equivalent of -1.75 D and -1.50 for the right and left eye, respectively. The subject was a 22-year-old young adult with no history of systemic and ocular diseases and used the best-corrected visual acuity (VA) 6/6 spectacle to correct the refractive error in daily activities. In this study, the refractive error was corrected at VA 6/6 with contact lenses to control the effect of vertex distance. The contact lens was to be optimally fitted in front of the subject's eyes.

The subject was initially exposed to a dark adaptation condition for five minutes to ensure no near effect before the measurement (Borsting *et al*., 2010). After the dark adaptation, the subject was seated in front of the WAM-5500 autorefractor and the subject's head was positioned properly on the autorefractor. The subject was instructed to look at the distant target at the midline in front of the subject's visual field and two minutes of continuous refractive measurement in this condition was taken via the dynamic mode of WAM-5500. The refractive state was assessed on the right eye while the subject fixated at a distance target at 6 m binocularly under full distance optical correction. Any measurement obtained during a blink was deleted and excluded in the data analysis and unusual high values as compared to the generally recorded values were considered noise and deleted. The micro fluctuation reporting was illustrated either in graphical figures or numerical values and descriptively compared.

Correlation Coefficient Measurement Procedure

In this preliminary study, the standard deviation of accommodation response approach was the simplest way to depict accommodation micro fluctuation and used during the earliest time in the measurement of micro fluctuation until now, the other two reporting approaches which were root means square and power spectrum analysis were correlated to the standard deviation approach. 30 young adults participated in this investigation with all subjects binocularly fixated at a distant cross target clearly at 6 m for two minutes. All measurement procedures followed the preliminary data collection procedure. To ensure that there was no bias in the accommodation micro fluctuation sampling measurement, confounding factors were controlled such as age, refractive status and experimental condition (Redondo *et al*., 2019; Logan *et al*., 2021). All subjects aged between 20 to 25 years and were emmetropic with a negligible refractive error range between -0.50 D to +0.50 D. The subjects had optimal distance VA of 6/6 or better with no known history of ocular disease or binocular vision problem. Based on the subjects' binocular amplitude of accommodation of 10 D and above with near point of accommodation of nearer than 6 cm, the binocular vision status of the subjects was in the normal age-expected range to ensure minimal influence on the accommodation response. In addition, similar measurement condition and instrumentation was applied in correlating to the three reporting approaches. Ethical approval from Universiti Teknologi MARA and written consent were taken prior to the study in ensuring adherence to Helsinki declaration.

Results

Preliminary Descriptive Findings

This study provided a descriptive illustration of three different reporting approaches for accommodation micro fluctuation from a single subject. Figure 1 illustrated the continuous time-series graph of accommodation micro fluctuation at distant viewing. Based on the continuous time-series graph of accommodation micro fluctuation, the mean accommodative responses can be obtained. The mean accommodation response for the subject was 0.04 D with a standard deviation of ± 0.1723 D. The mean response indicated accommodation lag at the distant viewing. Nevertheless, the 0.1723 D standard deviation described the variation in accommodation micro fluctuation. As for the variation, the accommodation fluctuated between -0.25 D minimum to 0.39 D maximum in dynamic accommodation response.

The root means square approach (RMS) was calculated by using the accommodation response data (Denieul & Simon, 1977) via the following formula of root mean square of standard errors as following:

$$RMS = \sqrt{1/n}\,(X_1^2 + X_2^2 + X_3^2 + \ldots\ldots. X_n^2)$$

n = sample data size

X = individual data

With all individual standard errors, the data was transformed into the square unit and all negative values of accommodation responses were analysed in meaningful values. The value of accommodation micro fluctuation for the subject was approximately 0.1719 D as presented in Table 1 which described the variation in accommodation micro fluctuation through RMS.

In the Fourier transform analysis approach, the data were transformed using Microsoft Excel. Under the data analysis plug-in, the Fourier analysis toolbar analyzed the measured data in a linear system. The analysis broke the signals into segments and allowed the investigation of each segment separately, based on the signal and sampling rate (Cooley & Tukey, 1965). The low-frequency component was based on a wide spectral range of less than 0.9 Hz while high-frequency component was based on a narrow spectral range of more than 1.1 Hz (Heron & Schor, 1995). The low-frequency component and high-frequency component are illustrated in Figure 2. The accommodation micro fluctuation was described within a limited range between 0 to 0.001 relative magnitude diopter in low component frequency, compared with high component frequency. Nevertheless, the difference between the Fourier Transform Analysis approach and the other two previous

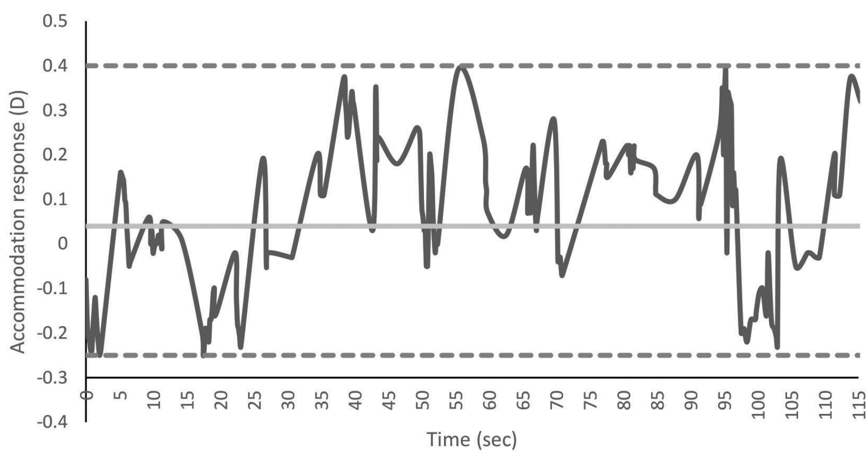

Figure 1: The continuous data presentation of the accommodation micro fluctuation over time. A solid horizontal line indicated the mean of accommodation responses. Dotted lines in the graph indicated the maximum and minimum responses

Table 1: Summary of root mean square approach (RMS) in the accommodation micro fluctuation calculation

Parameter	Value
Total square values of individual data	5.2278
Sample data size	177
Root mean square (RMS) formula	1/177 X (5.2278)
RMS of accommodation micro fluctuation	0.1719

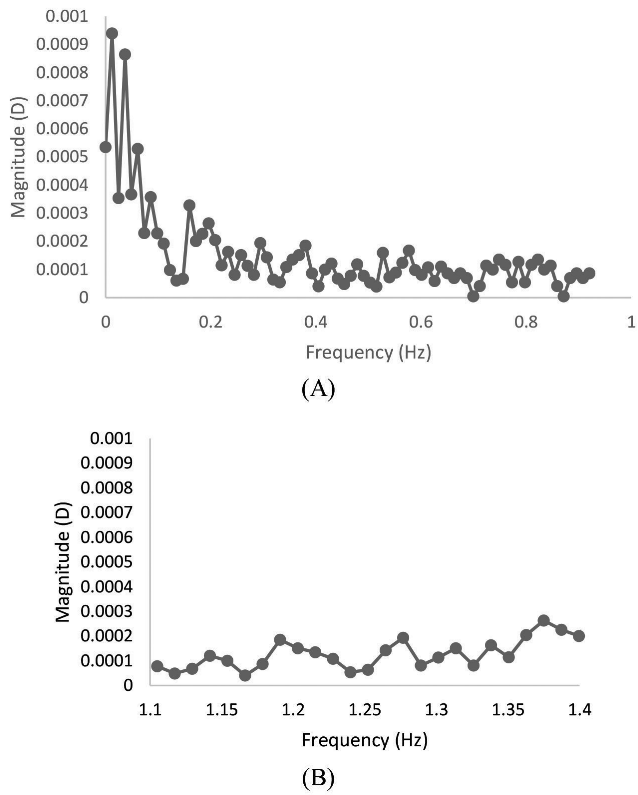

Figure 2: The spectrum analysis based on the Fourier transform approach of the accommodation micro fluctuation: (A) the low-frequency component, (B) the high-frequency component

approaches was that the micro fluctuation range was arranged in unit diopter (D) of relative magnitude as shown on y-axis.

Correlation Coefficient Findings

Based on Shapiro-Wilk normality test, the data were normally distributed ($p>0.05$). The mean of standard deviation (SD), root mean square (RMS) and Fourier Transform (FT) approaches were 0.2064 D (±0.07), 0.2061 D (±0.07) and 0.1037 D^2/Hz (±0.04), respectively. The correlation coefficient between RMS and SD was at 0.5776 ($p<0.01$). The regression between both RMS and SD approaches is illustrated in Figure 3. Subsequently, the correlation coefficient between FT and SD was at 0.4745 ($p<0.01$). The regression between both FT and SD approaches is illustrated in Figure 4. Lastly, the correlation coefficient between FT and RMS was 0.4726 ($p<0.01$). The regression between both FT and RMS approaches is illustrated in Figure 5.

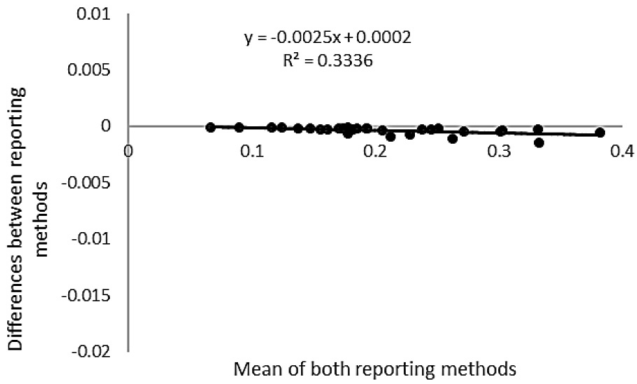

Figure 3: The scatter plot of regression between the RMS and SD reporting. Correlation R = 0.5776 (P<0.01), slope = -0.0025 (P<0.01), intercept = 0.0002 (P=0.28)

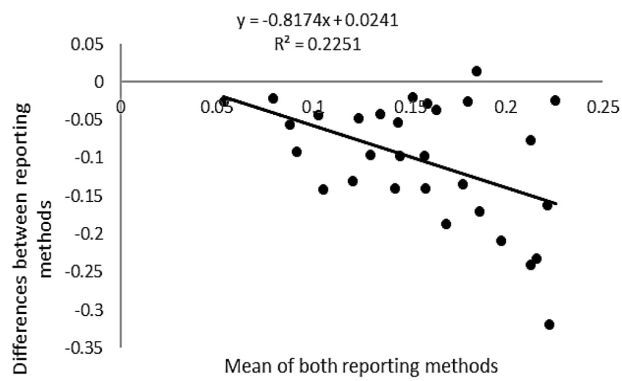

Figure 4: The scatter plot of regression between the FT and SD reporting. Correlation R = 0.4745 (P<0.01), slope = -0.8174 (P<0.01), intercept = 0.0241 (P=0.61)

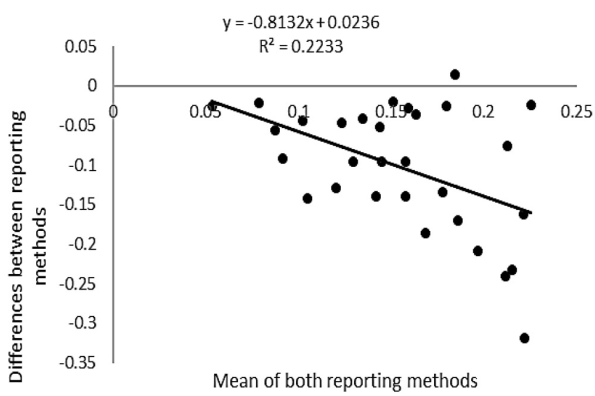

Figure 5: The scatter plot of regression between FT and RMS reporting. Correlation R = 0.4726 (P<0.01), slope = -0.8132 (P<0.01), intercept = 0.0236 (P=0.61)

Discussion

The simplest reporting approach for accommodation response variation is the standard deviation (SD) approach by considering the progressive changes of accommodation response according to a time-based curve. The progressive curve is usually plotted in which the accommodation micro fluctuation is acquired directly in addition to the mean accommodation response (Xu *et al*., 2009). Our study discovered that the accommodation micro fluctuation from the subject through the standard deviation approach was 0.1723 D, indicating an apparent variation of accommodation response. However, the standard deviation approach included both positive and negative values, therefore, it could negate and lessen the actual amount of micro fluctuation.

On the other hand, the root means square approach was calculated based on the standard deviation of the accommodation response (Plainis *et al*., 2005). It is also known as quadratic mean and is a statistical measure defined as the square root of the mean of the squares of a sample. In our study, the root means square (RMS) approach revealed almost identical micro fluctuation (0.1719 D) as compared to the standard deviation approach (0.1723 D). Although the difference was too small to be considered clinically influential as the in-market available ophthalmic lens was only produced at 0.25 D steps, the 0.01 D difference affected the positioning of the retinal conjugate point optically, particularly at a distance. From this direct descriptive comparison, the root means square approach was more ready to analyse the variation of accommodation response over time on the sinusoidal graph (Chen *et al*., 2019). The advantage of using the root means square approach is the accuracy of the result which was due to the number of samples measured on the signal, thus, it may be enough to have a long signal compared to the sampling rate (Denieul & Simon, 1977). This was done by considering that standard deviation may tend to inaccurately depict the actual amount of accommodation micro fluctuation. This was because the standard deviation approach findings included both positive and negative values which may negate and lessen the actual amount of micro fluctuation. Thus, the root means square had less chance to make an error in transforming the data. In addition, this root means square approach was still able to provide a single indication of the average amount of micro fluctuation in dioptre more specifically for a certain period (Anderson *et al*., 2010). Hence, the accommodation micro fluctuation was more appropriately depicted in the root mean square than the standard deviation.

The expression of micro fluctuation value using the Fourier transform (FT) approach is complex. In our study, the low-frequency component of the Fourier transform illustrated that the accommodation micro fluctuation from the same subject was between 0 to 0.001 relative magnitude dioptre. As Fourier transform approach analyses the temporal characteristics of the accommodation micro fluctuation using frequency components (Heron, 1995), it was divided into both low and high-frequency components (Campbell *et al*., 1959). Variation was apparent at the initial phase of the low-frequency component. Our finding showed that the micro fluctuation peaked at the initial low-frequency component phase. This was in agreement with previous studies which established that the low-frequency components have a wider band while the high-frequency components are narrower as shown through power spectrum analysis of the micro fluctuation waveform (Charman & Heron, 1988; Heron & Schor, 1995; van der Heijde, 1996).

The low-frequency component was present in the fluctuation of anterior chamber depth, lens thickness and vitreous length but not in the axial length, proving that only the crystalline lens was involved in the accommodation micro fluctuations (van der Heijde *et al*., 1996). Increases in the power of the low-frequency component had also been associated with larger ocular depth of focus from decreasing pupil size, decreasing target luminance and increasing blur (Day *et al*., 2009). In contrast, a small band of the high-frequency component was found in the recordings of vitreous and axial length, which appeared to correspond with heart rate and pulsation. This could be seen by the huge variation in response over time for the high-frequency component where the peak was suggested to be an artifact produced by the measurement instrument such as by the mechanical part resonating and moving in the high-frequency component bandwidth (Schultz *et al*., 2009). This artifact became the intrinsic biorhythm noise, produced by the heartbeat, breathing or other rhythmical physiological systems that had harmonic synchronization in the high-frequency component bandwidth.

In addition to the limited range of low-frequency Fourier transform, our findings were also in agreement with previous studies (Gray *et al*., 1993; van der Heijde *et al*., 1996) high-contrast (90% that relate low-frequency component with the accommodative response control and contributed to the steady-state accommodative response. The Fourier transform approach assesses the stationary spectrum and then transforms the micro fluctuation compatibly with the result based on waveform analysis. It uses the Fourier logarithmic changing process which involves only a data set in multiplication to the power of two and transforms a chosen set of sine waves into a square wave pattern. Thus, the square wave pattern can be further analysed by looking at the amplitudes and phases.

Due to the Fourier logarithmic change involved in the Fourier transform analysis to convert the sine waves into a square wave, the conversion is relatively complex and time-consuming. A square is represented as an infinite summation of sinusoidal waves, in which the amplitude alternates at a steady frequency between a fixed minimum and maximum values with the same duration at minimum and maximum (Iskander *et al*., 2004). The instantaneous transition between minimum to maximum of an ideal square wave in the actual biological and physical system may not be realizable as it is appropriate to only use the Fourier transform under the condition of a stationary spectrum (Li *et al*., 2022). To avoid transformation problems, the sampling rate had to be at least double the maximum frequency contained in the signal. Moreover, the Fourier transform computes an average of spectra of the signal over time. In the human system, the Fourier transform approach was commonly used to exemplify the physiological microtremor of low amplitude oscillation in the reflex mechanism controlling stretched muscle which is present in every muscle in the body such as in the ocular or even the control of vocal pattern (Patil *et al*., 2013).

Comparing the three reporting approaches descriptively from the same subject in our study, the Fourier transform approach involves lengthy transformational steps as compared to the standard deviation approach and root mean square approach. Nevertheless, the accommodation micro fluctuation value of the standard deviation approach and root mean square approach cannot be compared directly to the Fourier transform approach. This is because the micro fluctuation in Fourier transform approach displays the diopter of relative magnitude, not as the diopter of accommodation response as the standard deviation approach and root mean square approach.

In addition, this study showed that the root mean square and standard deviation approaches had higher correlation coefficients than the findings between the Fourier Transform and root mean square approaches and the findings between the Fourier transform and standard deviation approaches. The correlation coefficient indicated a good correlation between the root mean square and standard deviation approaches at 0.5776. Nevertheless, although the root mean square value was almost near to the standard deviation, there was still a difference between both values in reporting the accommodation micro fluctuation. As for the Fourier transform approach, it had moderate correlation with the standard deviation approach at 0.4745 and with the root mean square approach at 0.4726. With the assumption of constant micro fluctuation over time (Charman & Heron, 2015, non-stationary accommodation micro fluctuation incorporated both time and frequency domains to demonstrate changes in the micro fluctuation itself (Iskander *et al*., 2004) instead of the variation of the accommodation response. Even though it was more complex, a time-frequency plots of the micro fluctuation changes could be produced. However, there was a concern of any compromise in the transforming process between signal of the spectrum over time and frequency. Therefore, time-averaged approach as shown in the root mean square approach was beneficial in quantifying the optical quality of defocused image in the human eye (Iskander, 2014; Xu *et al*., 2019). This approach could be used to investigate future studies on ocular stability and ocular biometry such as changes during accommodation (Hughes *et al.*, 2020).

Conclusion

Based on our findings among all the three reporting approaches, the root means square approach reports the accommodation micro fluctuation more easily than transforming the data into frequency components. Furthermore, the root means square approach has fewer errors as compared to the standard deviation approach and is less complicated compared as compared to the Fourier transform approach. The root means square approach is highly recommended if the researchers intend to report the accommodation micro fluctuation as a whole outcome in the square function of a single number with better numerical accuracy, without having to isolate the low and high-frequency components. Furthermore, it was better correlated to the time-based standard deviation approach compared to the frequency-based Fourier transform approach. Nevertheless, the standard deviation approach seems to be the simplest way to depict accommodation micro fluctuation while the Fourier transform has the advantage to isolate the micro fluctuation frequency-based spectrum distribution of low and high-frequency components although it is the most complex approach. As various findings can be yielded using different reporting approaches, proper consideration should also be given to the instruments used to measure and report accommodation micro fluctuation, respectively.

Acknowledgements

The research was supported by the Ministry of Higher Education through the Fundamental Research Grant Scheme (Grant No. FRGS/1/2022/SKK06/UITM/01/1) and Universiti Teknologi MARA (UiTM).

References

Anderson, H. A., Glasser, A., Manny, R. E., & Stuebing, K. K. (2010). Age-related changes in accommodative dynamics from preschool to adulthood. *Investigative Ophthalmology & Visual Science*, *51*(1), 614-622. https://doi.org/10.1167/iovs.09-3653

Borsting, E., Tosha, C., Chase, C., & Ridder, W. H. (2010). Measuring near-induced transient myopia in college students with visual discomfort. *Optometry and Vision Science*, *87*(10). https://doi.org/10.1097/OPX.0b013e3181f31f4e

Campbell, F. W., Robson, J. G., & Westheimer, G. (1959). Fluctuations of accommodation under steady viewing conditions. *The Journal of Physiology*, *145*(3). https://doi.org/10.1113/jphysiol.1959.sp006164

Candy, T. R., & Bharadwaj, S. R. (2007). The stability of steady state accommodation in human infants. *Journal of Vision*, *7*(11), 4.1-416. https://doi.org/10.1167/7.11.4

Charman, W. N., & Heron, G. (1988). Fluctuations in accommodation: A review. *Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists)*, *8*(2), 153-164. https://doi.org/10.1111/j.1475-1313.1988.tb01031.x

Charman, W. N., & Heron, G. (2015). Microfluctuations in accommodation: An update on their characteristics and possible role, *Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists)*, *35*(5), 476-499. https://doi.org/10.1111/opo.12234

Chen, A.-H., Ahmad, A., Kearney, S., & Strang, N. (2019). The influence of age, refractive error, visual demand and lighting conditions on accommodative ability in Malay children and adults. *Graefe's Archive for Clinical and Experimental Ophthalmology*, *257*(9). https://doi.org/10.1007/s00417-019-04405-z

Cooley, J. W., & Tukey, J. W. (1965). An Algorithm for the machine calculation of complex fourier series. *Mathematics of Computation*, *19*(90). https://doi.org/10.2307/2003354

Day, M., Seidel, D., Gray, L. S., & Strang, N. C. (2009). The effect of modulating ocular depth of focus upon accommodation microfluctuations in myopic and emmetropic subjects. *Vision Research*, *49*(2). https://doi.org/10.1016/j.visres.2008.10.010

Denieul, P., & Simon, J. (1977). Optometre enregistreur des microfluctuations d'accommodation. *Vision Research*, *17*(9). https://doi.org/10.1016/0042-6989(77)90019-0

Gambra, E., Sawides, L., Dorronsoro, C., & Marcos, S. (2009). Accommodative lag and fluctuations when optical aberrations are manipulated. *Journal of Vision*, *9*(4), 1-15. https://doi.org/10.1167/9.6.4

Gray, L. S., Winn, B., Gilmartin, B., & Eadie, A. S. (1993). Objective concurrent measures of open-loop accommodation and vergence under photopic conditions. *Investigative Ophthalmology and Visual Science*, *34*(10), 2996-3003.

Gruning, C. F. (1985). Clinical management of nearpoint stress-induced vision problems. *Optometry and Vision Science*, *62*(6). https://doi.org/10.1097/00006324-198506000-00005

Heron, G. (1995). The fluctuations of accommodation and ageing. *Ophthalmic and Physiological Optics*, *15*(5), 445-449. https://doi.org/10.1016/0275-5408(95)00077-Q

Heron, G., & Schor, C. (1995). The fluctuations of accommodation and ageing. *Ophthalmic and Physiological Optics*, *15*(5), 445-449. https://doi.org/10.1016/0275-5408(95)00077-Q

Hughes, R. P. J., Read, S. A., Collins, M. J., & Vincent, S. J. (2020). Changes in ocular biometry during short-term accommodation in children. *Ophthalmic and Physiological Optics, 40*(5), 584-594. https://doi.org/10.1111/opo.12711

Hunter, J. D., Milton, J. G., Lüdtke, H., Wilhelm, B., & Wilhelm, H. (2000). Spontaneous fluctuations in pupil size are not triggered by lens accommodation. *Vision Research*, *40*(5), 567-573. https://doi.org/10.1016/S0042-6989(99)00200-X

Hynes, N. J., Cufflin, M. P., Hampson, K. M., & Mallen, E. A. H. (2022). The effect of image resolution of display types on accommodative microfluctuations. *Ophthalmic and Physiological Optics*, *42*(3), 514-525. https://doi.org/https://doi.org/10.1111/opo.12949

Iskander, D. R., Collins, M. J., Morelande, M. R., & Zhu, M. (2004). Analyzing the dynamic wavefront aberrations in the human eye. *IEEE Transactions on Biomedical Engineering*, *51*(11). https://doi.org/10.1109/TBME.2004.834254

Langenbucher, A., Huber, S., Nguyen, N. X., Seitz, B., Gusek-Schneider, G. C., & Küchle, M. (2003). Measurement of accommodation after implantation of an accommodating posterior chamber intraocular lens. *Journal of Cataract and Refractive Surgery*, *29*(4), 677-685. https://doi.org/10.1016/S0886-3350(02)01893-X

Leroux, C.-E., Leahy, C., Fontvieille, C., & Bardin, F. (2021). The random walk of accommodation fluctuations. *Biomedical Optics Express*, *12*(11). https://doi.org/10.1364/boe.433926

Li, L., Zhang, B., & Wang, Z. (2022). Comparison of accommodation and accommodative micro-fluctuation after implantable collamer lens and LASIK surgery for myopia. *BMC Ophthalmology*, *22*(1), 8. https://doi.org/10.1186/s12886-021-02217-6

Logan, N. S., Radhakrishnan, H., Cruickshank, F. E., Allen, P. M., Bandela, P. K., Davies, L. N., Hasebe, S., Khanal, S., Schmid, K. L., Vera-Diaz, F. A., & Wolffsohn, J. S. (2021). IMI Accommodation and Binocular Vision in Myopia Development and Progression. *Investigative Ophthalmology & Visual Science, 62*(5), 4. https://doi.org/10.1167/iovs.62.5.4

Monticone, P. P., & Menozzi, M. (2011). A review on methods used to record and analyze microfluctuations of the accommodation in the human eye. *Journal of the European Optical Society*, *6*(2011). https://doi.org/10.2971/jeos.2011.11003

Motlagh, M., & Geetha, R. (2019). Physiology, Accommodation. In *StatPearls [Internet]*. Treasure Island, StatPearls Publishing.

Niwa, K., & Tokoro, T. (1998). Influence of spatial distribution with blur on fluctuations in accommodation. *Optometry and Vision Science*, *75*(3), 227-232. https://doi.org/10.1097/00006324-199803000-00029

Patil, V. P., Nayak, K. K., & Saxena, M. (2013). Voice Stress Detection. *International Journal of Electrical, Electronics and Computer Engineering*, *2*(2).

Plainis, S., Ginis, H. S., & Pallikaris, A. (2005). The effect of ocular aberrations on steady-state errors of accommodative response. *Journal of Vision*, *5*(5), 466-477. https://doi.org/10.1167/5.5.7

Redondo, B., Vera, J., Luque-Casado, A., García-Ramos, A., & Jiménez, R. (2019). Associations between accommodative dynamics, heart rate variability and behavioural performance during sustained attention: A test-retest study. *Vision Research, 163*, 24-32. https://doi.org/10.1016/j.visres.2019.07.001

Schultz, K. E., Sinnott, L. T., Mutti, D. O., & Bailey, M. D. (2009). Accommodative fluctuations, lens tension and ciliary body thickness in children. *Optometry and Vision Science: Official Publication of the American Academy of Optometry*, *86*(6), 677-684. https://doi.org/10.1097/OPX.0b013e3181a7b3ce

Sheppard, A. L., & Davies, L. N. (2010). Clinical evaluation of the Grand Seiko Auto Ref/Keratometer WAM-5500. *Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists)*, *30*(2), 143-151. https://doi.org/10.1111/j.1475-1313.2009.00701.x

van der Heijde, G. L., Beers, A. P. A., & Dubbelman, M. (1996). Microfluctuations of steady-state accommodation measured with ultrasonography. *Ophthalmic and Physiological Optics*, *16*(3), 216-221. https://doi.org/10.1016/0275-5408(95)00051-8

Winn, B., Charman, W. N., Pugh, J. R., Heron, G., & Eadie, a S. (1989). Perceptual detectability of ocular accommodation microfluctuations. *Journal of the Optical Society of America. A, Optics and Image Science*, *6*(3), 459-462. https://doi.org/10.1364/JOSAA.6.000459

Xu, D., Chen, X., Yan, J., Jiang, J., Qu, J., & Lü, F. (2009). Accommodation response fluctuation in myopia during sustained near work. *Chinese Journal of Ophthalmology*, *45*(1), 50-55. https://doi.org/10.3760/cma.j.issn.0412-4081.2009.01.011

Xu, J., Lu, X., Zheng, Z., Bao, J., Singh, N., Drobe, B., & Chen, H. (2019). The effects of spatial frequency on the accommodative responses of myopic and emmetropic Chinese children. *Translational Vision*

Science & Technology, *8*(3), 65. https://doi.org/10.1167/tvst.8.3.65

Zhu, M., Collins, M. J., & Iskander, D. R. (2006). The contribution of accommodation and the ocular surface to the microfluctuations of wavefront aberrations of the eye. *Ophthalmic & Physiological Optics: The Journal of the British College of Ophthalmic Opticians (Optometrists)*, *26*(5), 439-446. https://doi.org/10.1111/j.1475-1313.2006.00373.x