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Validity of heart rate variability measured with Apple Watch compared to laboratory measures

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Validity of heart rate variability measured with Apple Watch compared to laboratory measures

A thesis submitted in partial satisfaction of the requirements for the Masters degree

in

Public Health

by

Sydney Paquita Sharp

Committee in charge:

Professor Job Gideon Godino, Chair

Professor John Belletiere

Professor Andrea LaCroix

2021

The Thesis of Sydney Paquita Sharp is approved, and it is acceptable in quality and form publication on microfilm and electronically:

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LIST OF ABBREVIATIONS

HRV	HEART RATE VARIABILITY
BPM	BEATS PER MINUTE
HR	HEART RATE
SA	SINO-ATRIAL
ANS	AUTONOMIC NERVOUS SYSTEM
CNS	CENTRAL NERVOUS SYSTEM
PNS	PARASYMPATHETIC NERVOUS SYSTEM
SNS	SYMPATHETIC NERVOUS SYSTEM
CV	CARDIOVASCULAR
CVD	CARDIOVASCULAR DISEASE
ECG	ELECTROCARDIOGRAM
PPG	PHOTOPLETHYSMOGRAPHY
EPARC	EXERCISE AND PHYSICAL ACTIVITY RESOURCE CENTER
MAPE	MEAN ABSOLUTE PERCENTAGE ERROR

ACKNOWLEDGEMENTS

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ABSTRACT OF THE THESIS

Validity of heart rate variability measured with Apple Watch compared to laboratory measures

by

Sydney Paquita Sharp

Masters Degree

in

Public Health

University of California San Diego, 2021

Professor Job Gideon Godino, Chair

Background: We assessed the test validity of the Apple Watch’s measure of HRV by comparing it with HRV measured via Biopac 3 lead ECG.

Methods: We recruited 58 young adults (aged 20- 51 years) from San Diego, CA, US. HRV was measured under the four following conditions during the visit: 1) at rest in a supine position, 2) sitting while talking, 3) sitting while watching a movie clip, and 4) sitting before and after walking. To guarantee the Apple Watch and Biopac 3 lead ECG recordings aligned, a synchronized countdown was conducted for each condition, with event markers electronically placed on the Biopac 3 lead ECG recording when the Apple Watch Breathe app began and ended. Test validity was assessed using the Bland-Altman method, and the combination of both precision and accuracy were estimated using Lin's correlation coefficient.

Results: The highest level of agreement and concordance between devices occurred during rest. Near perfect agreement was observed for measures of the R-R interval and BPM, with mean absolute percentage errors of 1.03% and 4.50 %, respectively. Moderate levels of agreement and concordance for N-N intervals, PNN50, and %PNN50 were only achieved at rest.

Conclusion: The Apple Watch provides a high level of validity for measuring R-R intervals and BPM in healthy adults. More refined measures of HRV, such as N-N intervals, were only moderately acceptable when taken at rest. Further research is needed to determine if the Apple Watch's HRV measures offer a significant opportunity for the surveillance of CVD risk.

INTRODUCTION

Defined as the beat-to-beat variation in heart rate (i.e., the duration of the R–R interval), heart rate variability (HRV) has become an important physiological biomarker that may lead to early detection and diagnosis of various cardiovascular diseases typically occurring later in life.[1,2] HRV results from numerous physiological mechanisms which regulate heart rate (HR). The heart beat originates at the sino-atrial (SA) node of the heart, where specialized cells produce electrical impulses generating heart muscle contractions.[1,3] The SA node is continuously controlled by the autonomic nervous system (ANS), where the resulting regulatory effect is HR.[4] The ANS is an efferent system transmitting impulses from the central nervous system (CNS) to secondary organs.[1,5,6] It controls mechanisms such as constriction and dilation of blood vessels, and contraction and relaxation of smooth muscle in various organs.[1,5,6] It is divided into two branches: the parasympathetic and sympathetic nervous systems. The parasympathetic nervous system (PNS) is also known as the body's rest and digest function; it is concerned with conservation and restoration of energy, resulting in decrease HR.[1,7] The sympathetic nervous system (SNS) is the body's fight or flight response. it allows the body to respond to challenges, increasing HR.[1,8] Balance between these two systems changes in response to internal and external stimuli.

Overall, HRV reflects the collective impact of SNS and PNS activity on HR, serving as a measurable indicator of cardiovascular (CV) health and disease prognosis.[1,9] Analysis of HRV is useful in assessing overall cardiac health and regulation of the ANS. High HRV is associated with lower cardiovascular disease (CVD) incidence[10], lower mortality risk[11], and lower risk for dementia and cognitive decline[12], all indicators of healthy aging. Inversely, low HRV predicts

CVD incidence and mortality in older adults, independent of traditional risk factors, such as left ventricular size and function.[10,11] Furthermore, experimental evidence suggests that HRV increases in a dose-response manner after as few as 6-months of exercise training.[13] Taken together, these findings suggest that HRV can be conceptualized as a modifiable factor that can reflect overall cardiovascular health and healthy aging.

To date, large-scale measurement of HRV has been prohibitive. HRV analysis has been conventionally performed in a laboratory environment on inter-beat intervals gathered from R waves in electrocardiograms (ECG).[14] In the free-living environment, measurement has typically required the use of an expensive and activity limiting Holter monitor. However, recent advances in technology have resulted in the proliferation of low-cost, non-invasive wearable devices that typically include photoplethysmography (PPG) sensors that use a light source and a photodetector at the surface of skin to measure volumetric changes in peripheral blood circulation that are the result of the heart beating.[15] Thus, they can be used to indirectly measure multiple components of the physiology of the heart, including HR, resting or maximal heart rate, and HRV.

Given that PPG sensors have been incorporated into widely available wrist-worn devices such as the Apple Watch, there is now a possibility for widespread and continuous measurement of HRV in large numbers of individuals. At present, Apple Watch sales have surpassed 100 million[16] and represent nearly 40% of the smartwatch market share.[17] Despite the ubiquity of the Apple Watch, there is a dearth of independent research studies which have examined its validity for measuring HRV. One laboratory-based study among 20 healthy volunteers (the age and sex of the participants were not reported) showed promising results, with 90% concordance between HRV measured via the Apple Watch and the Polar H7 chest belt.[18] This study was limited by a small sample size and lack of demographic or anthropometric characterization of the study sample. Additionally, it did not interrogate various conditions under which HRV measurement with the Apple Watch are likely to occur (e.g., seated at a desk while working on a computer).

In the present study, we assessed the test validity of the Apple Watch's measure of HRV by comparing it with HRV measured via Biopac 3 lead ECG, a research-grade device, among 60 healthy adults. We investigated measures taken under a variety of controlled conditions (e.g., while resting in a supine and sitting position, engaging in conversation) in a laboratory under the direct supervision of trained staff. This represents an important step towards being able to make an informed decision about whether or not the Apple Watch's measure of HRV could be used within clinical practice and epidemiological research. Given that HRV is increasingly being used in cardiovascular disease risk stratification and as a marker of overall cardiac health, the potential to measure it accurately, cheaply, and conveniently via a consumer-level wearable in a free-living environment has important implications for its widespread adoption.

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METHODS

Participants

Potential participants were recruited by word of mouth and via listservs (i.e., email). Research staff screened potential participants, and they were excluded if they were pregnant, had diabetes, or had any heart, lung, or autoimmune disease. Eligible participants were between the ages of 20 and 50 years old and were willing to abstain from alcohol for 72 hours and from caffeine and nicotine for 24 hours prior to testing. We recruited an approximately equal ratio of male and female participants, as well as an equal number of participants from each age group (~20 per decade).

Procedures

All study procedures were approved by the University of California, San Diego Institutional Review Board (approval number 200085). Each participant provided written informed consent and attended one 2-hour laboratory visit at the Exercise and Physical Activity Resource Center (EPARC).

Upon arrival, participants were asked to complete four self-administered questionnaires which included information about socio-demographics, health history, smoking history, medications, physical activity, sedentary behaviors, and sleep habits. EPARC staff measured blood pressure (systolic blood pressure (SBP)/diastolic blood pressure (DBP)) and heart rate (beats per minute (BPM)) using an automatic blood pressure monitor. If the first and second measurement differed by more than 5mm Hg, then the first reading was discarded and the average of reading two and three were used. Height (to the nearest 0.1cm) and weight (to the nearest 0.1kg) were then measured using a stadiometer and a calibrated digital scale (Seca, Chino, CA). Height and weight were measured with participants clothed but without shoes, taking two measurements. A third measure was taken if measurements differed by more than 1% and the average of the two measures that differed by less than 1% was used. Lastly, hip and waist circumference (to the nearest 0.1cm) were measured by EPARC staff with the participant standing on a 12” box, having their feet together and weight evenly distributed, with arms across their chest. The maximum extension of the buttocks and the narrowest portion of the torso were measured twice using a Gulick II Tape, with a third measurement being taken if the measurements differed by more than 1% and the average of the two measures that differed by less than 1% was used.

Participants were instrumented with two measurement devices: Biopac 3 lead ECG (criterion device) and the Apple Watch. The Biopac 3 lead ECG was selected as the reference standard for measuring HRV. It was deployed by placing the electrodes in a chest-mounted pattern with one electrode under each clavicle and the third on the lower left rib cage. The Apple Watch was placed on participants’ left wrist. To ensure the best reading, proper fit required skin contact on the top of the wrist with the electrical and optical heart sensors being snug but comfortable with room for the skin to breathe. The watch utilizes PPG technology to record HRV, using green LED lights and light- sensitive photodiodes to detect blood flow in the wrist.

We utilized the Breathe application (app) on the watch, as it is currently the only way to ensure a real time HRV measure. When using the Breathe app, the duration can last between one and five minutes, with the number of breaths per minute ranging from four to ten. However, we found that the actual Breathe app is 12 seconds longer than the whole minute picked (i.e., a five-minute session would be five minutes and 12 seconds). For our study, we programmed the Breathe app to complete 7 breaths per minute and chose the five- and one-minute durations.

Haptic vibrations were turned off to not distract the participant. To guarantee the Apple Watch and Biopac 3 lead ECG recordings aligned, a synchronized countdown was conducted for each condition, with event markers electronically placed on the Biopac 3 lead ECG recording when the Apple Watch Breathe app began and ended.

HRV was measured under the four following conditions during the visit: 1) at rest in a supine position, 2) sitting while talking, 3) sitting while watching a movie clip, and 4) sitting before and after walking. Due to the sampling capabilities of the Apple Watch, five minutes of HRV were measured for the first three conditions, and two one-minute segments for the last condition. The Biopac 3 lead ECG continuously measured throughout each condition. At the start of the first condition, the participant laid supine in a quiet room for 10 minutes, while also attached to a portable indirect calorimeter (COSMED, Trentino, Italy) which measured continuously. Immediately following the 10 minutes, the Apple Watch and Biopac 3 lead ECG gathered data for five minutes. Once data was collected, the portable indirect calorimeter (COSMED, Trentino, Italy) was removed. The talking condition was then conducted with the participant being seated and data being gathered for the full five-minute conversation. While remaining seated, a five-minute clip from the film Harry Potter was shown and data were collected for the full five-minutes. Lastly, the participant was re-instrumented with the portable indirect calorimeter (COSMED, Trentino, Italy), as well as a hip ActiGraph. The participant completed two 10-meter walks to gather stride count, the distance covered when you take two steps, then completed a 2.5-minute walk at “usual pace” around an indoor track (20m/lap). The distance traveled was measured and recorded. HRV data was collected while being seated with the Apple Watch and Biopac 3 lead ECG for one minute immediately prior to, and one minute following the 2.5-minute walk. The hip ActiGraph, and portable indirect calorimeter (COSMED, Trentino, Italy) measured continuously before, during, and after the 2.5-minute walk.

Table 1. LABORATORY TEST CONDUCTED FOR COMPARISON OF APPLE WATCH AND BIOPAC 3 LEAD ECG DEVICE.

Category	**Activity**	**Event**	**Time**	**Description**
Lying Down	Rest as Recommended	1	5 minutes	Lying quietly
Sitting	Conversation	2	5 minutes	Engaging in a conversation
	Video Clip	3	5 minutes	Watching a Harry Potter clip
	Pre- Walk	4	1 minute	Sitting quietly prior to 2.5-minute walk
	Post- Walk	5	1 minute	Sitting quietly after 2.5-minute walk

For each Apple Watch measurement, the compatible iPhone was examined in real-time to ensure that the watch recorded properly. If the watch did not record HRV, another measurement was conducted for the condition for a maximum of two recordings per condition. Raw RR data was extracted from the Breathe app and stored in the compatible iPhone's Personal Health Record. This data was then exported using Apple's Health App in XML format, which was then transferred to an excel database created by EPARC research staff. Biopac 3 lead ECG data was downloaded using AcqKnowledge 4.4 software, where each cycle was found and copied into the same excel data base. Event markers on the Biopac 3 lead ECG, which were flagged during each of the four conditions at the beginning and end of the Breathe session, were also copied into the excel database serving as an alignment tool for the Biopac 3 lead ECG and Apple Watch. A final summary table comparing the events of the Biopac 3 lead ECG to the Apple Watch was generated from the excel data base analyzing matched beats and R-R differences. All data were associated with a unique participant identifier (e.g., 00001) and downloaded and stored on secure, password protected EPARC servers.

Metrics of Interest

Table 2. DATA DICTIONARY DEFINING VARIABLES OF INTEREST FOR HRV MEASUREMENT.

Variable of Interest	Definition
#_of_valid_r-r	Average number of valid R-R, defined as under 1500 milliseconds (ms)
r-r**_average**	Average length of time of valid R-R (ms)
r-r_sd	Standard deviation of the length of valid R-R (ms)
n-n_average	Average length of valid N-N (ms), defined as the length of time between two consecutive valid R-R
n-n_sd	Standard deviation of the length of valid N-N (ms)
#_pnn_50	Number of valid N-N that are greater than or equal to 50ms
%_pnn_50	Percentage of all valid N-N that are greater than or equal to 50ms
#_of_missed_beats	Total number of missed beats derived from any R-R greater than 1500ms, each 1000ms over 1500ms adds an additional missed beat (i.e., R-R of 4000ms = 3 missed beats)
Avg_bpm	Average beats per minute

Statistical Analysis

Demographic and anthropometric characteristics of the participant sample were analyzed using univariate descriptive statistics. Test validity was evaluated using the Bland-Altman method to analyze the agreement between the Apple Watch and reference device. The limits of agreement were specified as the mean of the discrepancies ±1.96 times the standard error of the differences. The corresponding Bland-Altman plot visualized how agreeable the devices of measurement were represented by the mean of the differences by the means of the measures, with the limits of agreement. Mean absolute percentage error (MAPE) was computed as the average of absolute differences among the measures, divided by the applicable research-grade measure, multiplied by 100. The combination of both precision and accuracy were estimated using Lin's correlation coefficient, which was visualized on a scatter plot. The aforementioned metrics were calculated for each measure and condition of interest.

This material is currently being prepared for submission for publication. Sharp, Sydney; Belletiere, John; LaCroix, Andrea; Godino, Job. "Validity of heart rate variability measured with Apple Watch compared to laboratory measures". The thesis author was the primary author of this paper.

RESULTS

From February 2021 to June 2021, a total of 58 participants (26 males and 32 females) completed all study protocols and were included in data analyses. The mean (SD) age was 33.5 yr (8.81 yr), mean (SD) height was 172 cm (9.02 cm), mean (SD) weight was 73.5 kg (14.0 kg), and mean (SD) BMI was 24.9 (3.99) (Table 3).

TABLE 3. PARTICIPANT CHARACTERISTICS.	
N	58 (100)
AGE (YR)	
20-29	21 (36.2)
30-39	20 (34.5)
40-49	17 (29.3)
SEX	
FEMALE	32 (55.2)
MALE	26 (44.8)
HISPANIC ORIGIN	10 (17.2)
ETHNICITY	
WHITE	36 (62.1)
AFRICAN AMERICA	1 (1.7)
ASIAN	17 (29.3)
AMERICAN INDIAN	1 (1.7)
NATIVE HAWAIIAN	0 (0)
OTHER	3 (5.2)
HEIGHT (CM), MEAN (SD)	171.5 (9.02)
WEIGHT (KG), MEAN (SD)	73.5 (14.0)
BMI, MEAN (SD)	24.9 (3.99)

R-R Interval

Figure 1 shows the results of Bland-Altman analyses with corresponding plots and Lin's correlation coefficient analyses with corresponding plots for the R-R interval. The R-R intervals for each condition resulted in the highest levels of agreement between devices. Both walking conditions had the largest disagreement, with mean absolute percentage errors of 5.62% and 5.81% respectively. The smallest disagreement was during the resting condition with a mean absolute percentage error of 1.03%.

N-N Interval

Figure 2 shows the results of Bland-Altman analyses with corresponding plots and Lin's correlation coefficient analyses with corresponding plots for the N-N interval. Once again, the resting condition had the smallest disagreement with a mean absolute percentage error of 15.1%. The largest disagreement took place during the conversation portion, with a mean absolute percentage error of 45.5%.

%PNN50 Intervals

Figure 3 shows the results of Bland-Altman analyses with corresponding plots and Lin's correlation coefficient analyses with corresponding plots for %PNN50 intervals. These analyses resulted in the largest outliers of mean absolute percentage error of the study of 116% for the talking condition and 154% for the video condition respectively. The resting condition had the smallest disagreement with a mean absolute percentage error of 36.6%.

PNN50 Intervals

Figure 4 shows the results of Bland-Altman analyses with corresponding plots and Lin's correlation coefficient analyses with corresponding plots for the number of PNN50 intervals. On average, these analyses resulted in the least agreement between devices. The smallest disagreement occurred during the post-walk condition, with a mean absolute percentage error of 51.2%. The largest disagreement was observed during the conversation condition with a mean absolute percentage error of 76.9%.

BPM

Figure 5 shows the results of Bland-Altman analyses with corresponding plots and Lin's correlation coefficient analyses with corresponding plots for BPM. The largest disagreement was during the video condition which produced an outlier mean absolute percentage error of 74.4%. The smallest disagreement was during the resting condition, with a mean absolute percentage error of 4.50%.

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DISCUSSION

The aim of this study was to assess the validity of the Apple Watch's measure of HRV compared to the reference standard of the Biopac 3 lead ECG in a healthy population of adults. It is one of the first studies to investigate the validity of the Apple Watch's measurement of HRV in a variety of controlled laboratory conditions designed to mimic free-living conditions such as while resting, talking, watching a film, and before and after walking. We observed that when comparing HRV measures against the research-grade device, its validity for each condition were most accurate for R-R intervals and BPM.

For R-R intervals, on average the mean absolute percentage error was less than 4% for all conditions. These results are similar to other studies for the Apple Watch, presenting reliability and agreement among R-R intervals.[18] Next to R-R, BPM had the most accurate results with an average mean absolute percentage error of 19.6% for all conditions.

The resting condition produced the most favorable results. Since the Breathe app was created to remind individuals to take time to breathe each day, guiding individuals through a sequence of deep breaths, it is not shocking that the resting condition recorded the best results across all measures. The resting condition would most closely mimic the atmosphere in which the Breathe app was intended to be used, since it was designed to encourage individuals to set aside a few minutes a day to relax.

The biggest discrepancies occurred when analyzing the %PNN50 intervals. The average mean absolute percentage error was 79.7%, which was about 20 times higher than R-R intervals. Since PNN50 intervals and %PNN50 intervals are calculated using the differences among successive N-N intervals[19], they reflect similar trends. The three analyses of N-N intervals, PNN50 intervals, and %PNN50 intervals resulted in the least agreeable outcomes reflected by the large average mean absolute percentage error of 31.4%, 65.4%, and 79.7% respectively. Concordance for these conditions were the lowest.

Data outliers occurred for mean absolute percentage error during analysis of %PNN50, as well as BPM. A very large discrepancy occurred in %PNN50 intervals during the talking and video condition with errors of 116% and 154% respectively, being three times higher than other conditions. During BPM analysis, the outlier occurred during the video condition, once again, with an error of 74.4%. This was approximately 13 folds higher than the mean absolute percentage error of other conditions. The results for the talking condition could have been affected by an individual's respiratory system as they talked affecting blood flow and thus HRV detection in the Apple Watch, as well as by an individual's tendency to speak and concurrently move their hands resulting in movement of the Apple Watch when it is supposed to be stationary. The video portion on the other hand, could have triggered an emotional response resulting in a change of BPM and %PNN50 intervals. Despite these outliers, HRV measurements of R-R intervals and BPM from the Apple Watch aligned well with the reference device.

With the promising results of R-R intervals and BPM of this study, Apple Watches potentially offer a significant opportunity for the surveillance of CVD and the development of interventions to reduce CVD risk. This is important because the population of older Americans is projected to nearly double from 49 million to 95 million by 2060, owing partly to declines in CVD mortality over the past half century.[20] Successful medical and public health interventions have focused primarily on preventing CVD events, but as CVD remains the leading cause of death in the US, novel intervention targets are needed to promote healthy cardiovascular aging. HRV and accurate prescription of relative exercise intensity are two potential targets. Having access to a continuously monitored HR could offer significant opportunities to better understand the role that HRV plays in long-term CV health, offering new insights into population health. Having access to wearable sensors to help monitor CV health could allow for population health to steadily progress with technology in areas such as stress management, athletic performances, and clinic care.

Our study had some limitations. One major limitation was the reliability of the Apple Watch's HRV recording while forcing the Breathe app. The limited recordings could have been a result of the Apple Watch positioning, not having good skin contact on the wrist, movement of the arm and wrist, or could have been affected by the participants' skin perfusion. This would make HRV measurements difficult in low or moderate exercise. Further research is needed to determine the optimal position of watch placement on the wrist for successful measurement and reliability of the watch. Furthermore, our findings are not generalizable to free-living context since they were associated with a laboratory-based protocol. More research is needed for the Apple Watch's HRV measure in a free-living context to determine its validity for use in interventions, epidemiologic studies or personal use. Lastly, since our sample was a convenient, non-clinical population with an emphasis on young adults, our results may not be generalizable to older populations. For this reason, further research on the Apple Watch is needed in older adults.

On the other hand, our study included numerous strengths. It was one of the first studies to objectively measure HRV using two devices, one being a wrist-worn device. The protocol also included a variety of controlled conditions, exposing how the Apple Watch operates under different circumstances. Lastly, unlike other Apple Watch validity studies, our study included stratification across different age decades, which improves the generalizability of our results across a variety of ages.

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CONCLUSION

A valid, economical product that accurately measures HRV among young adults is important to further cardiovascular health regarding risk stratification and disease identification. This is among the first studies to evaluate the validity of the Apple Watch's measure of HRV to a reference device. The high level of validity for measuring R-R intervals and BPM on the Apple Watch provide strong implications for clinical and epidemiological research. With the general population having access to an accurate wrist-worn health device, new interventions could target real-time applications aimed at lowering CVD. The next step would be to test validity in a free-living environment and on an older population to determine if the Apple Watch's HRV measures offer a significant opportunity for the surveillance of CVD risk.

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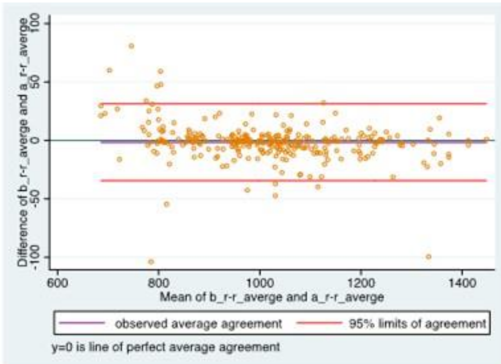
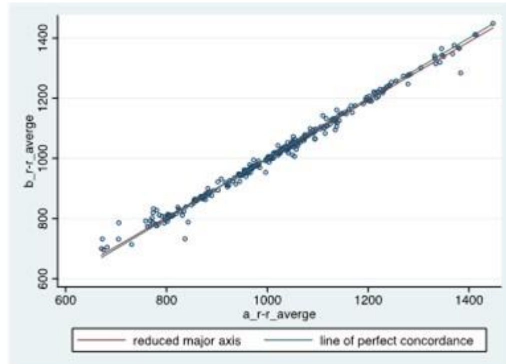
APPENDIX

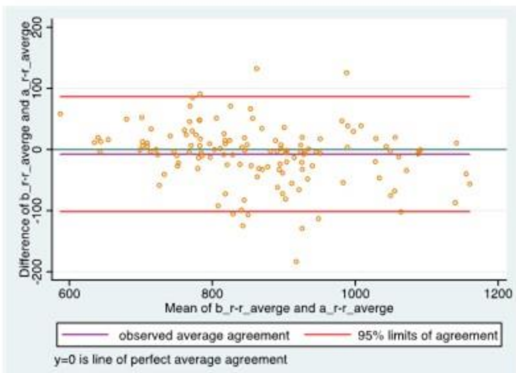


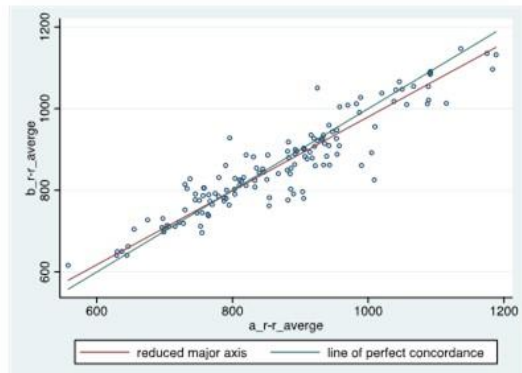


Mean Bias = -1.70, SD = 16.79; 95% LAO = -34.61 to 31.21

Rho = 0.99; SE = 16.79; 95% CI = .993 to .996

Condition 1. Rest as Recommended

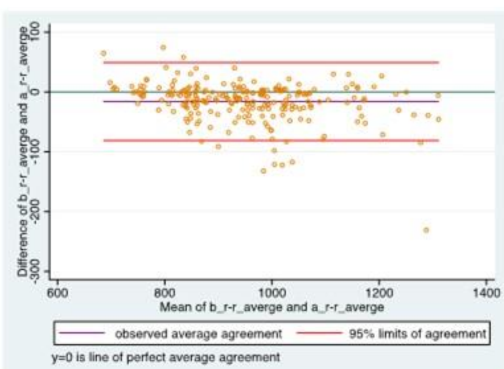


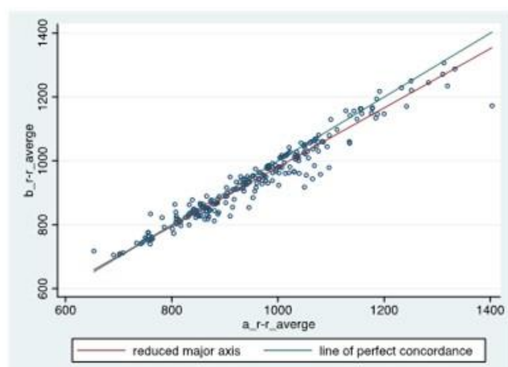


Mean Bias = -7.60, SD = 48.06; 95% LAO = -101.80 to 86.60

Rho = 0.92; SE = .01; 95% CI = .897 to .946

Condition 2. Conversation



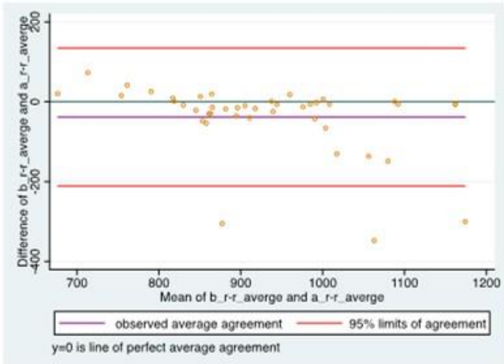


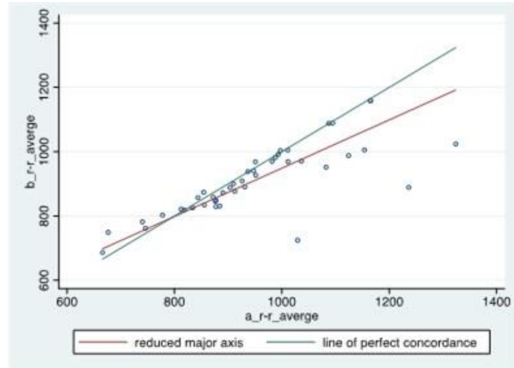
Mean Bias = -16.24, SD = 33.25; 95% LAO = -81.40 to 48.93

Rho = 0.96; SE = .005; 95% CI = .950 to .969

Condition 3. Video Clip

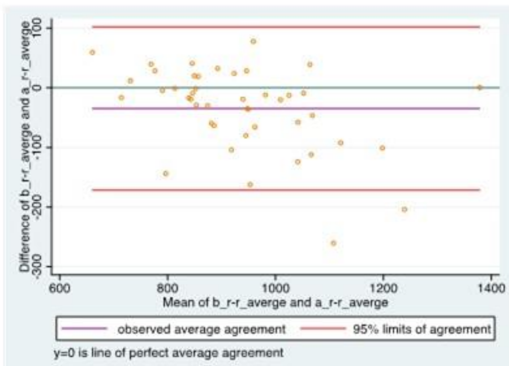
Figure 1. R-R Intervals.

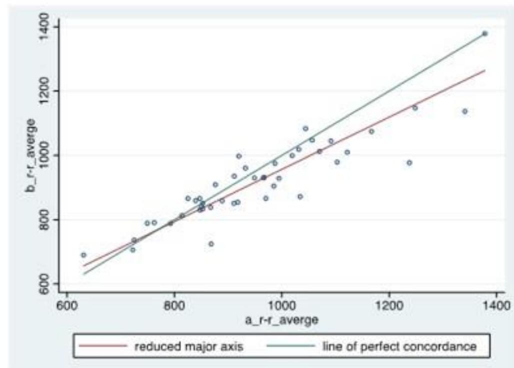




Mean Bias = -38.24, SD = 88.12; 95% LAO = -210.94 to 134.46 Rho = 0.72; SE = .066; 95% CI = .594 to .851

Condition 4. Pre- Walk

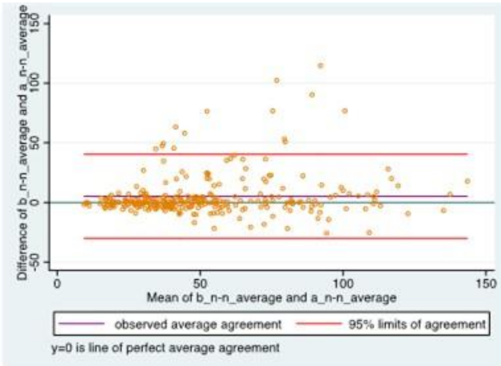


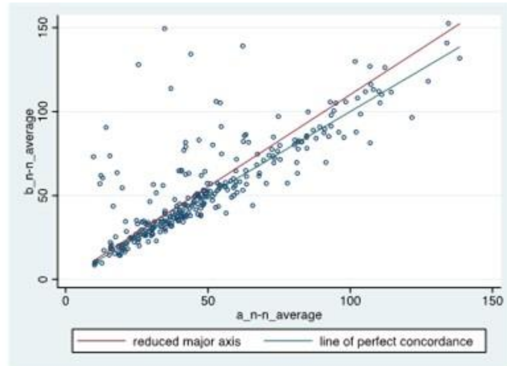


Mean Bias = -34.67, SD = 69.82; 95% LAO = -171.52 to 102.19 Rho = 0.862; SE = .035; 95% CI = .793 to .931

Condition 5. Post- Walk

Figure 1 (continued).

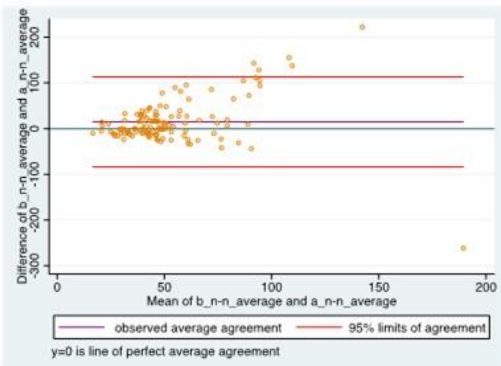


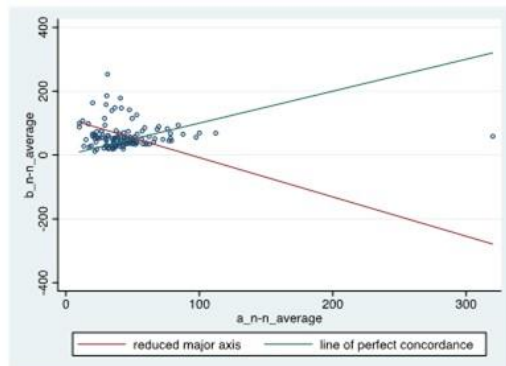


Mean Bias = 5.14, SD = 17.94; 95% LAO = -30.016 to 40.298

Rho = 0.789; SE = .022; 95% CI = .746 to .832

Condition 1. Rest as Recommended

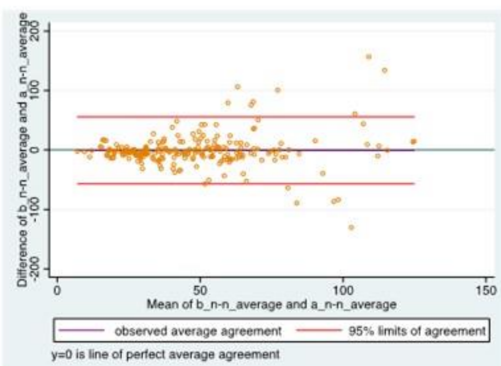


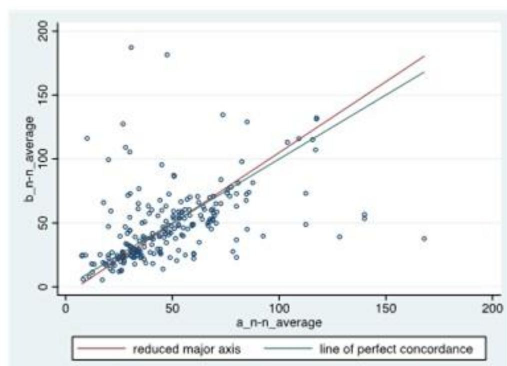


Mean Bias = 14.91, SD = 50.07; 95% LAO = -83.21 to 113.04

Rho = -0.024; SE = .081; 95% CI = -.183 to .134

Condition 2. Conversation



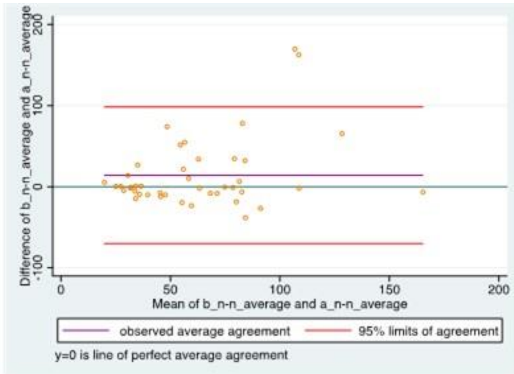


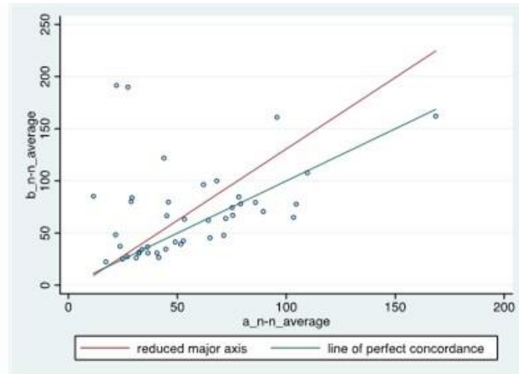
Mean Bias = -0.637, SD = 28.815; 95% LAO = -57.112 to 5.839

Rho = 0.453; SE = .052; 95% CI = .351 to .556

Condition 3. Video Clip

Figure 2. N-N Intervals.

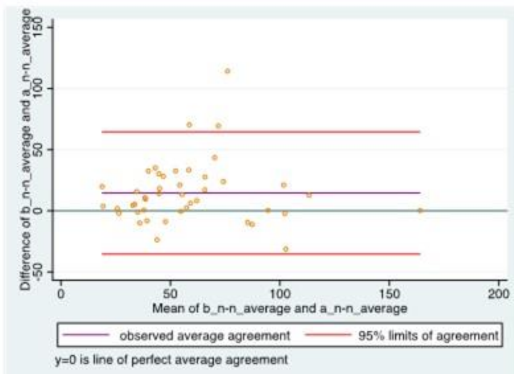


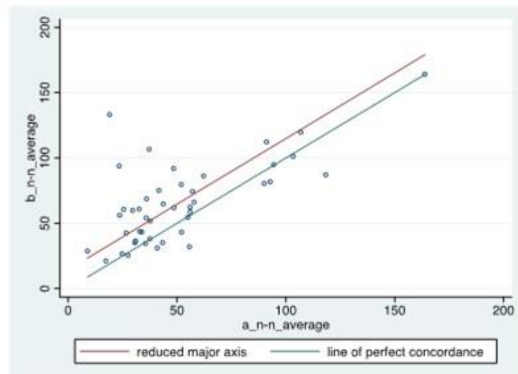


Mean Bias = 14.08, SD = 42.96; 95% LAO = -70.11 to 98.27

Rho = 0.324; SE = .124; 95% CI = .081 to .567

Condition 4. Pre- Walk



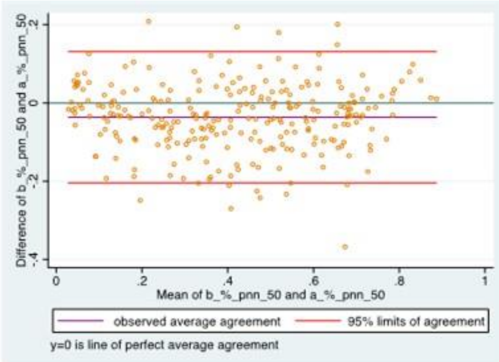


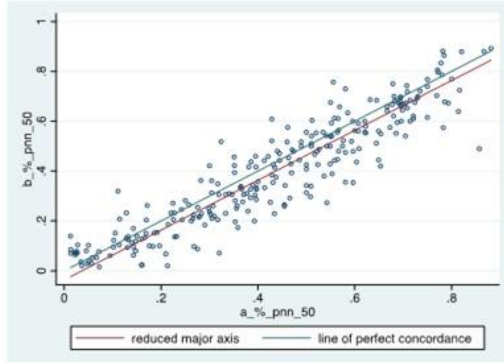
Mean Bias = 14.62, SD = 25.51; 95% LAO = -35.34 to 64.62

Rho = 0.601; SE = .090; 95% CI = .425 to .776

Condition 5. Post- Walk

Figure 2 (continued).

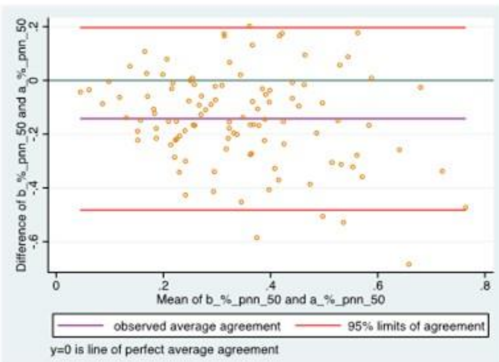


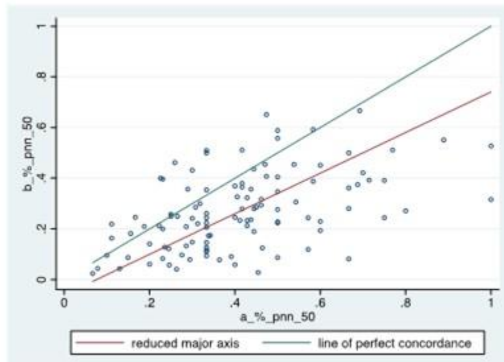


Mean Bias = -0.37, SD = 0.086; 95% LAO = -.204 to .131

Rho = 0.913; SE = .010; 95% CI = .894 to .933

Condition 1. Rest as Recommended

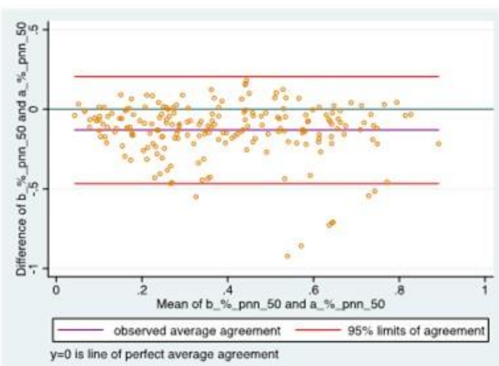


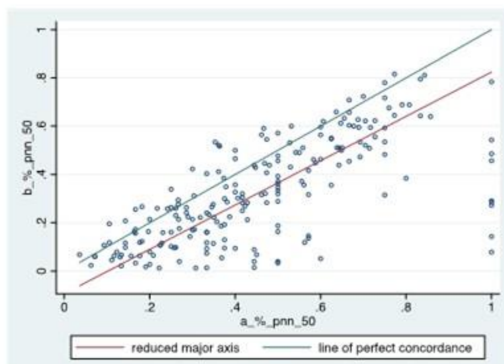


Mean Bias = -0.143, SD = 0.173; 95% LAO = -.482 to .197

Rho = 0.366; SE = .062; 95% CI = .245 to .487

Condition 2. Conversation



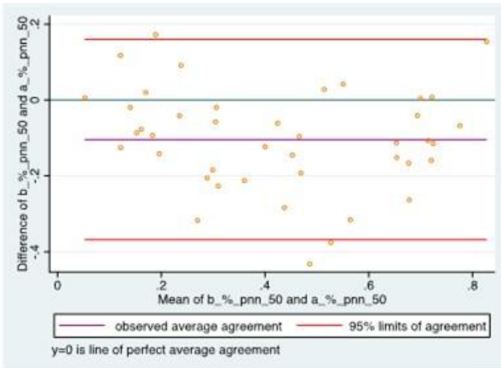


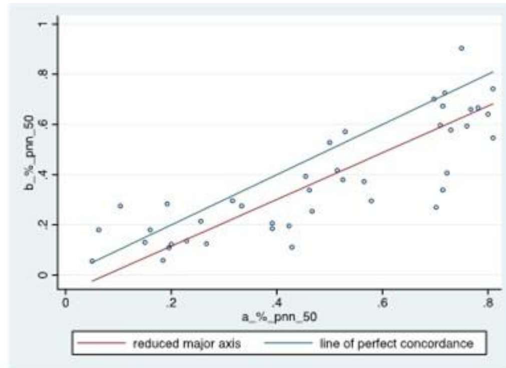
Mean Bias = -0.131, SD = 0.172; 95% LAO = -0.468 to 0.206

Rho = 0.587; SE = .039; 95% CI = .510 to .664

Condition 3. Video Clip

Figure 3. %PNN50 Intervals.

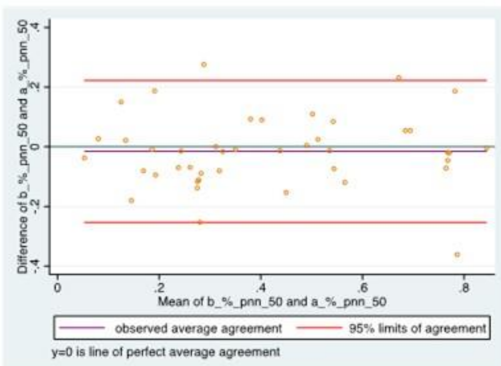


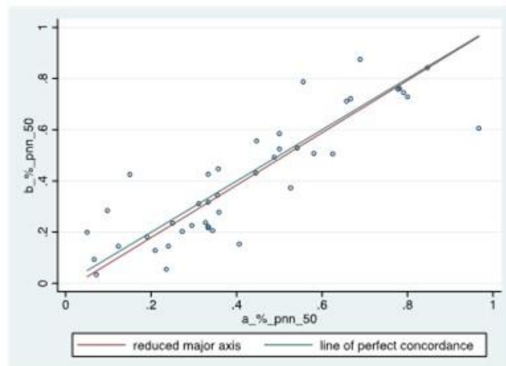


Mean Bias = -0.104, SD = 0.135; 95% LAO = -0.368 to 0.160

Rho = 0.755; SE = .061; 95% CI = 0.635 to .875

Condition 4. Pre- Walk



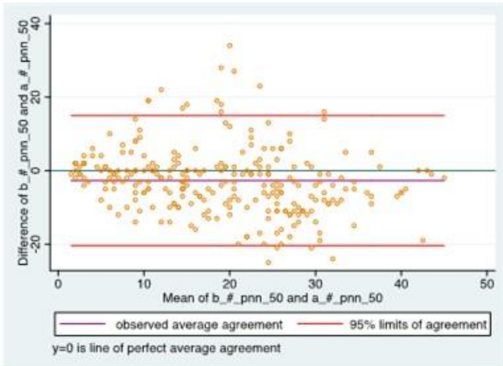


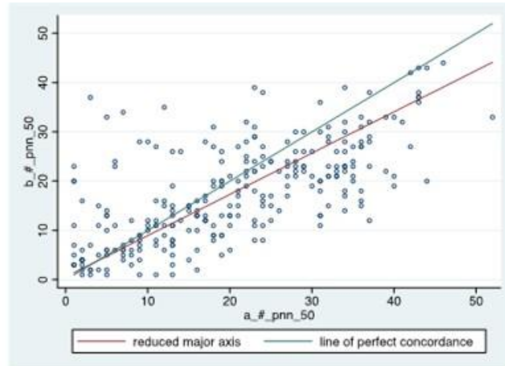
Mean Bias = -0.015, SD = 0.121; 95% LAO = -.253 to .223

Rho = 0.866; SE = .039; 95% CI = .790 to .942

Condition 5. Post- Walk

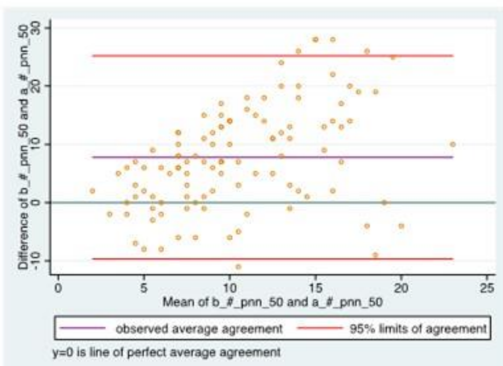
Figure 3 (continued).

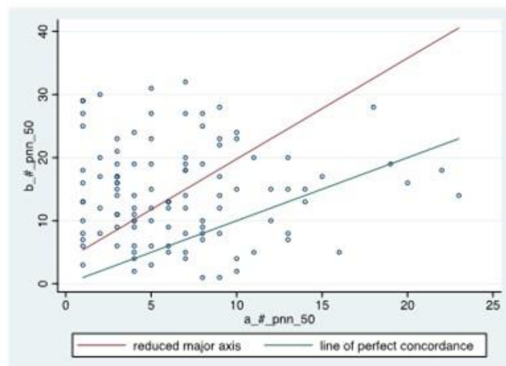




Mean Bias = -2.740, SD = 9.028; 95% LAO = -20.433 to 14.954 Rho = 0.644; SE = .034; 95% CI = .577 to .711

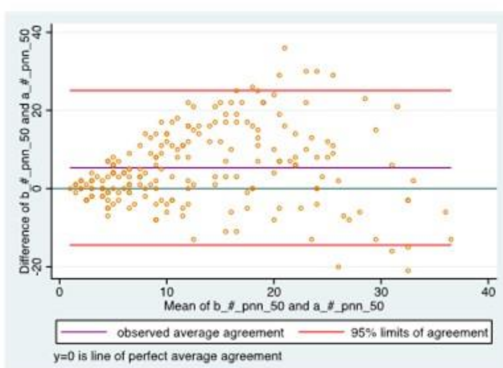
Condition 1. Rest as Recommended

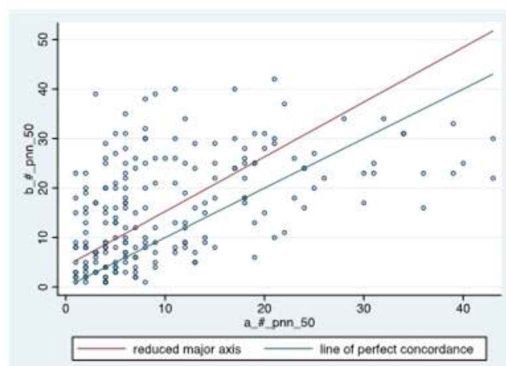




Mean Bias = -7.752; SD = 8.888; 95% LAO = -9.669 to 25.173 Rho = 0.005; SE = .049; 95% CI = -.091 to .102

Condition 2. Conversation

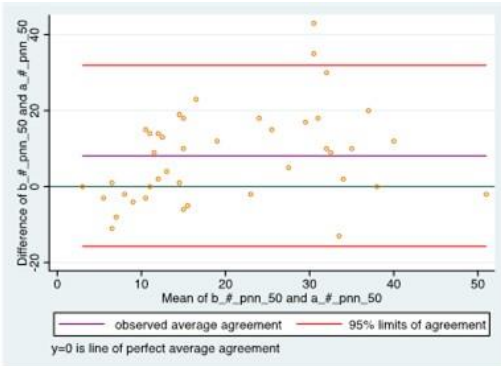


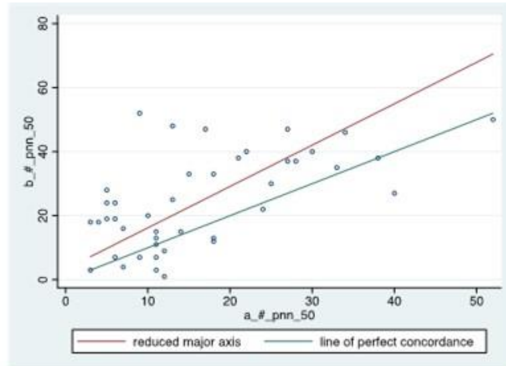


Mean Bias = 5.332, SD = 10.078; 95% LAO = -14.422 to 25.085 Rho = 0.418; SE = .051; 95% CI = .319 to .518

Condition 3. Video Clip

Figure 4. PNN50 Intervals.

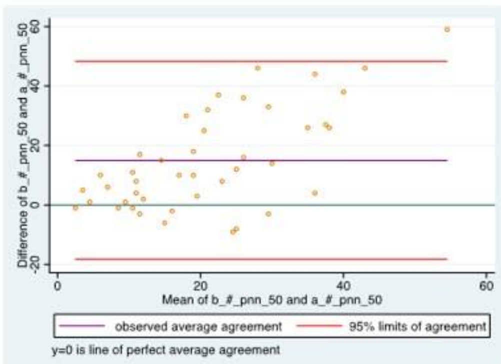


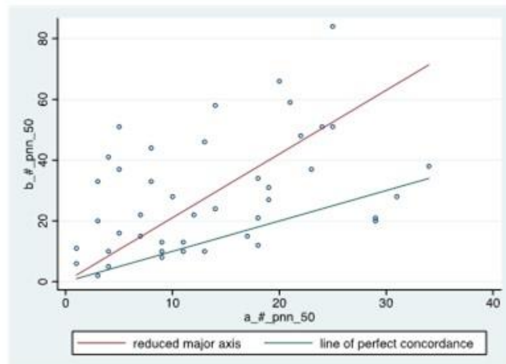


Mean Bias = 8.095, SD = 12.143; 95% LAO = -15.705 to 31.895

Rho = 0.486; SE = .099; 95% CI = .292 to .679

Condition 4. Pre- Walk



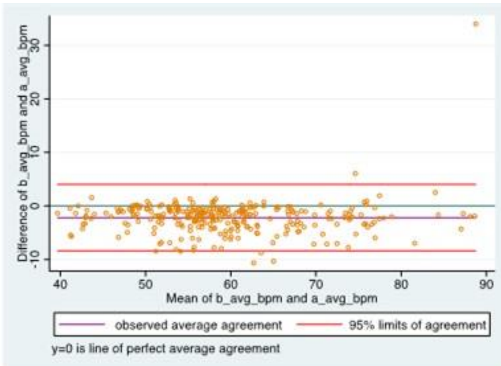


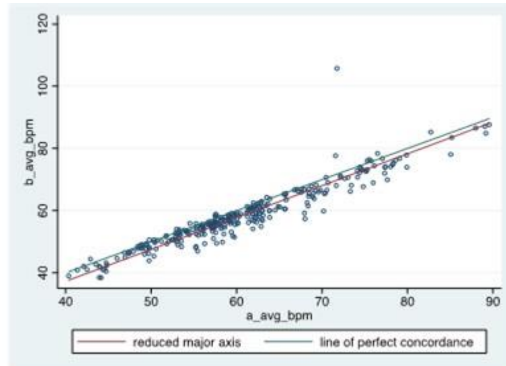
Mean Bias = 15.023, SD = 16. 952; 95% LAO = -18.201 to 48.248

Rho = 0.215; SE = .076; 95% CI = .065 to .365

Condition 5. Post- Walk

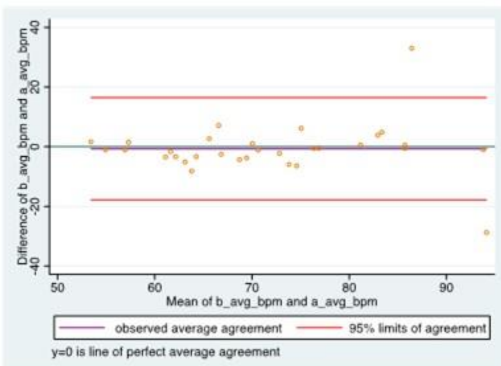
Figure 4 (continued).

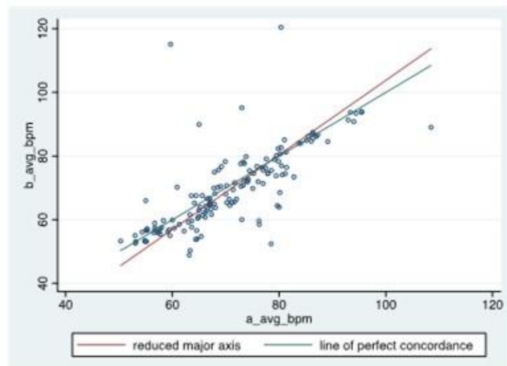




Mean Bias = -2.198, SD = 3.171; 95% LAO = -8.414 to 4.017   Rho = 0.925; SE = .008; 95% CI = .909 to .941

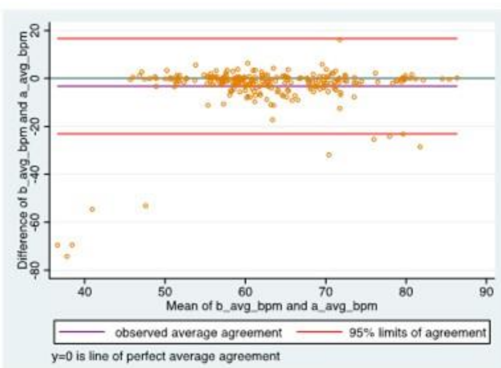
Condition 1. Rest as Recommended

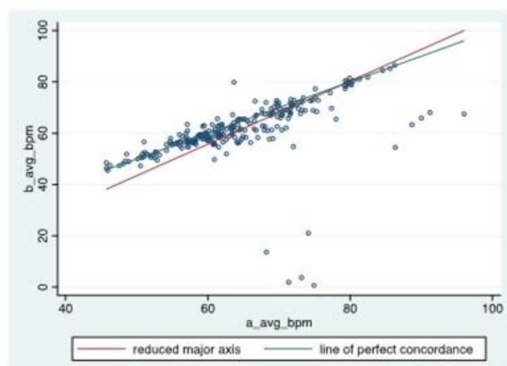




Mean Bias = -1.196, SD = 8.454; 95% LAO = -17.766 to 15.374   Rho = 0.737; SE = .037; 95% CI = .665 to .809

Condition 2. Conversation

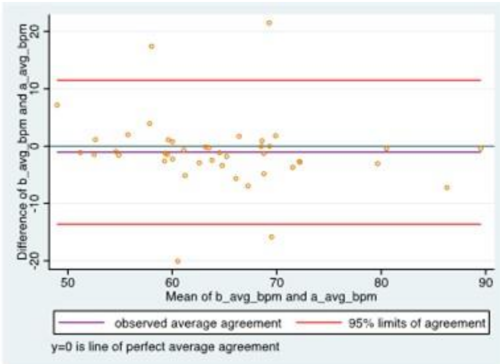


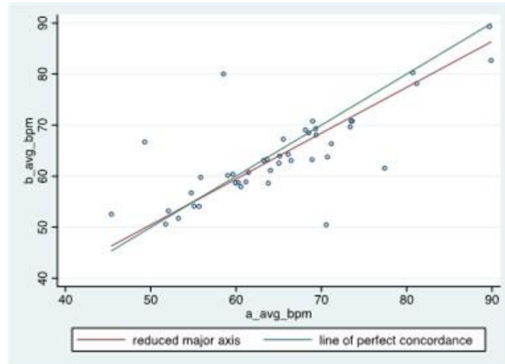


Mean Bias = -3.218, SD = 10.137; 95% LAO = -23.087 to 16.651   Rho = 0.486; SE = .045; 95% CI = .398 to .575

Condition 3. Video Clip

Figure 5. BPM.

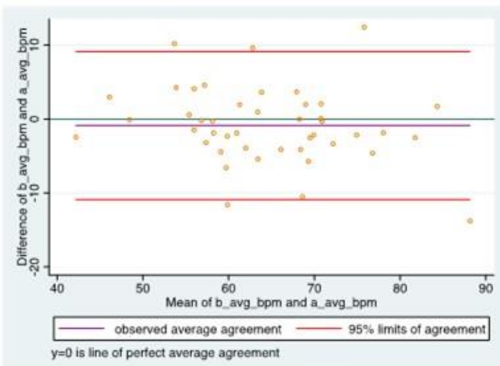


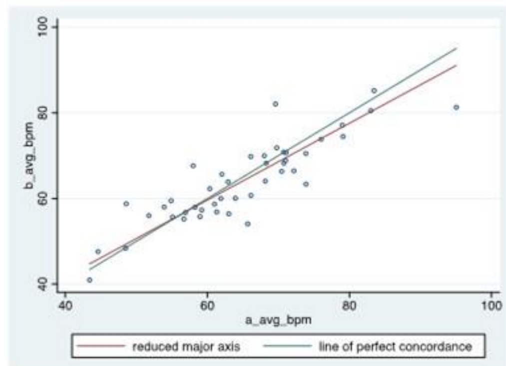


Mean Bias = -1.065, SD = 6.409; 95% LAO = -13.626 to 11.495

Rho = 0.756; SE = .066; 95% CI = 0.627 to .885

Condition 4. Pre- Walk





Mean Bias = -0.879, SD = 5.11; 95% LAO = -10.895 to 9.136

Rho = 0.868; SE = .037; 95% CI = .795 to .941

Condition 5. Post- Walk

Figure 5 (continued).

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