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Assessing the Validity and Reliability of Several Heart Rate Monitors in Wearable Technology While Mountain Biking

Bryson Carrier

ASSESSING THE VALIDITY AND RELIABILITY OF SEVERAL HEART RATE MONITORS IN WEARABLE TECHNOLOGY WHILE MOUNTAIN BIKING

By

Bryson Carrier

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Bryson Carrier

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Department of Kinesiology and Nutrition Sciences

James Navalta, Ph.D.
Examination Committee Chair

Graham McGinnis, Ph.D.
Examination Committee Member

Tedd Girouard, M.S.
Examination Committee Member

Benjamin Burroughs, Ph.D.
Graduate College Faculty Representative

Kathryn Hausbeck Korgan, Ph.D.
Graduate College Dean

Abstract

This study sought to assess the validity and reliability of several heart rate (HR) monitors during mountain biking (MTB), compared to the Polar H7® HR monitor, used as the criterion device. **Methods**: A total of 20 participants completed two MTB trials wearing 6 HR monitors (1 criterion, 5 test devices). HR was recorded on a second-by-second basis for all devices analyzed. After data processing, validity measures were calculated, including 1. Error analysis: mean absolute percentage errors (MAPE), mean absolute error (MAE), and mean error (ME), and 2. Correlation analysis: Lin's concordance correlation coefficient (CCC) and Pearson's correlation coefficient ®. Validity was determined for overall HR as well as stratified HR data based on 5 HR zones. Thresholds for validity were set at MAPE<10% and CCC>0.7. Reliability measures were also determined comparing trial 1 to trial 2 via two statistical tests: 1. Intra-class correlation coefficient (ICC) and 2. Coefficient of variation (CV). The predetermined reliability threshold was set at an ICC of >0.7 and a CV<10%. **Results**: The only device that was found to be valid during mountain biking was the Suunto Spartan Sport watch with accompanying HR monitor, with a MAPE of 0.66% and a CCC of 0.99 for the overall, combined data. **Conclusion**: If a person would like to track their HR during mountain biking, for pacing, training, or other reasons, the devices best able to produce valid results are chest-based, wireless ECG monitors, secured by elastic straps to minimize the movement of the device, such as the Suunto chest-based HRM.

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Introduction

The development of fitness trackers and other wearable technology designed for health and fitness purposes is growing in popularity and sophistication every day. Wearable devices have been the top fitness trend four out of the last five years (it was number three in 2018), as determined by health and fitness professionals throughout the world *(1-5)*. Wearable devices can be used in a range of exercise formats, from running, cycling, swimming, rowing, weightlifting, and mountain biking, to name a few. They have the ability to measure or estimate a variety of physiological and physical variables, such as step count, energy expenditure, VO_2max, lactate threshold, heart rate, stride length, vertical oscillation, ground contact time, blood oxygen saturation (via pulse oximetry), and many others. As these devices have gained acceptance among the general population, they have also caught the interest of athletes, sports scientists, and researchers *(6-9)*. These wearable devices have the potential to revolutionize physiological research, due to their prevalence and constant monitoring of the user's physiology *(10)*. However, in order to properly use these devices, independent validation needs to take place to determine the device's accuracy and ability to properly measure or estimate each variable *(11, 12)*.

Each physiological or physical variable tracked by these devices ranges in the precision of the measurements or estimates, with aspects such as step-count, run cadence, stride length and VO_2max generally being accurate *(11, 13-15)*, and energy expenditure and vertical oscillation being less accurate *(11-13)*. One of the most common measurements for devices to record is heart rate (HR), and its performance in recording HR during exercise has had mixed results, with wireless, chest-based ECG monitors showing high levels of accuracy and reliability *(16-18)* and wrist-based sensors being less accurate *(17, 19, 20)*. Wearable technology designed to measure

HR comes in an array of different devices that can include chest straps, wrist-based watches and sensors, smart bras, earbuds, rings, and forearm or bicep-based devices. These devices are designed to be used in all environments, measuring HR throughout the day. There have been an abundance of studies utilizing the laboratory to validate the ability of wearable technology to measure/estimate variables like HR, energy expenditure, and step-count while performing common exercise modalities like running or biking *(21, 22)*. However, there is a lack of both validation studies and reliability studies that take place in field, outdoor, or applied settings for wearable technology *(11)*. This study will be important because it evaluates both validity and reliability, something that has been established by multiple authors to be an important yet lacking aspect in the technology literature *(11, 12, 15)*.

Mountain biking is a popular and growing sport, enjoyed recreationally and professionally *(23, 24)*. It was conceived back in the late 1970s and became an Olympic sport in 1996 *(25)*. It involves both uphill and downhill biking on dirt roads and can be physiologically demanding, especially on the uphill segments *(26, 27)*. It is an activity that many people do on a regular basis for exercise. Mountain biking athletes can use wearable devices to help make training decisions and tracking physiological and physical variables. They may use it to determine heart rate, energy expenditure, altitude gain, distance travelled, and many other aspects, as stated earlier. According to a recent systematic review, it is important to test these devices in many different environments and exercise formats, to better understand their limitations and available use cases *(11)*. Because of these two aspects, 1) the growing popularity of mountain biking, and 2) the need to validate wearable devices in a range of exercise formats and environments, mountain biking was determined to be a satisfactory condition for this study. Therefore, the purpose of this study was to determine the validity and reliability of several HR monitors while mountain biking outdoors. As the nature of validity testing is, essentially, to determine its accuracy, we adopt the null hypothesis as our own, $H_o = H_a$.

Methods

Twenty apparently healthy participants volunteered for this study (10 male, 10 female, age = 26.3 ± 6.6 years, height = 171.8 ± 8.0cm, mass = 73.9 ± 19.0kg, reported as mean ± SD) (see table 1). Participants met at a predetermined destination (McCullough Hills Trailhead, Henderson, NV, USA) and were asked to fill out an informed consent document that was previously approved by the University of Nevada, Las Vegas Biomedical Sciences Institutional Review Board. Weight was then taken via digital scale (Omron HBF-516b, OMRON Corp., Kyoto, Japan), and self-reported height and mountain biking experience was recorded. Researchers then explained to the participants that they would be expected to perform two self-paced 3.22 km (two mile) mountain biking trials while donning the fitness trackers and HR monitors. There was a total of six devices worn by each participant (one criterion and five devices being tested), two wrist worn devices (fēnix 5, Polar A360), one forearm device (Rhythm+), one earbud device (Jabra), and two chest strap devices (Polar H7, Suunto) (see table 2). Participants could ride their own mountain bike if they owned one, if not, they were provided a bike and helmet.

Table 1. Demographic Data

Total Subjects	**Average Age (yrs)**	**Average Height (ft)**	**Average Height (in)**	**Average Height (cm)**
20	26.3 ± 6.6	5.6 ± 0.3	67.7 ± 3.2	171.8 ± 8.0
Average Weight (lbs)	Average Weight (kg)	Total Participants (Males)	Total Participants (Females)	Average Activity Level (min/week)
162.67 ± 41.8	73.9 ± 19.0	10	10	351.0 ± 183.3
Total MTB Experience (Low)	Total MTB Experience (Moderate)	Total MTB Experience (High)		
17	3	0		

Demographic data of the participants included in the present study.

Table 2. Device and Company Information

Brand	Device	Company Information
Garmin	fēnix® 5	Garmin Ltd., Schaffhausen, Switzerland
Jabra	Elite Sport Earbuds	Jabra, Copenhagen, Denmark
Suunto	Spartan Sport Watch + Chest HRM	Suunto Oy, Vantaa, Finland
Scosche	Rhythm+	Scosche Industries Inc., Oxnard, CA, USA
Polar	H7 Heart Rate Monitor	Polar Electro Inc., Woodbury, NY, USA
Polar	A360 Fitness Tracker	Polar Electro Inc., Woodbury, NY, USA

Company information of each device used in the current study.

The trail that was used for this study had a 48m elevation change and desert terrain consisting of dirt and rock (see figure 1). Participants performed the same route, twice, to test for reliability, with 10 minutes of rest between trials. The criterion device used for this study was the Polar H7 heart rate monitor, which contains a single, flexible plastic sensor (2.4x27.9cm) worn at the level of the xiphoid process, with the strap being wrapped around the torso by an elastic band. The trail was marked with small orange yard flags for the majority of participants, however, due to operational convenience, not all participants had the trail marked. Due to this, some participants departed from the set pathway. This was anticipated, and they were instructed that they needed to go one mile, as recorded by the Garmin fēnix® 5 on their wrist, then turn around. For the reliability test, they were instructed to use the same route completed previously. Approximately 3 of the 20 participants used an alternate route than the set path, but all were able to use the same route for both trials. There was a technical error with the data recording, and the data for the criterion device was not collected for four participants, leaving the available data for analysis at 16 participants and 32 trials.

Figure 1. Elevation Profile of McCullough Hills Trail

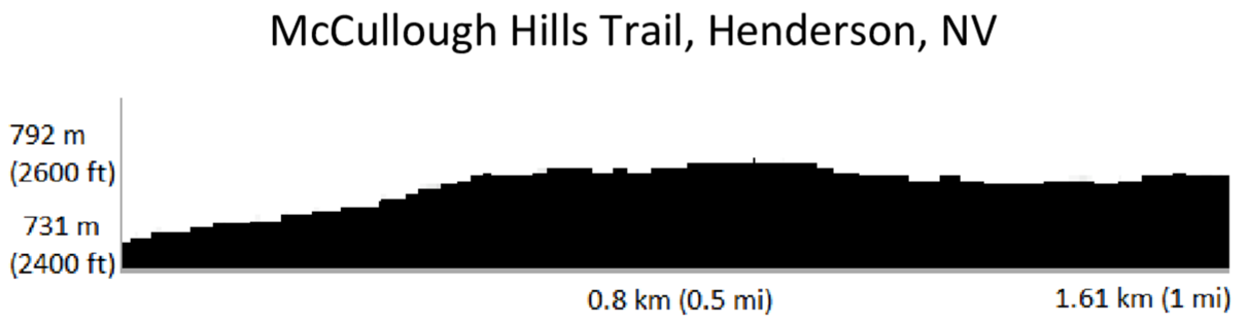


Figure originally published in Navalta et al., 2020 and used with permission.

Data Processing and Analysis

Data Processing

After the data was extracted from each device, the files were converted to CSV format (if needed) and joined by the date and time stamp via custom Python code in Homebrew (Software Freedom Conservancy, Brooklyn, NY, USA). All devices produced results in a second-by-second format, and values were expressed as beats per minute (bpm). The data was then trimmed at the beginning and end to account for varying start and end times of the devices due to each device being started and stopped manually by the researchers. There was an average of 26 seconds removed from each end. After the data was trimmed, a quality assessment of the criterion device data was performed, and where null data, "0" values, or abnormal data in the criterion device was found, the data at that time was removed from all devices. Finally, non-physiological data points were removed from any device (bpm>220). There was a total of 35,774 lines of data after data processing was completed. See table 3 for a breakdown of the data removal steps that were taken.

Table 3. Data Removal Steps

Data Points from Original
37,674
Data Points After Trimming Ends
36,034
Total Data Points Removed From Trimming Ends
1,640
Total Time Removed from Trimming Ends in Entire Dataset (min)
27.33
Avg Time Removed From Each Trial (sec)
51.25
Avg Time Removed from Each End of Trial (sec)
25.63
Total Data Points Removed Due to Non-Physiological Values (>220 bpm)
13 (all from Rhythm+ Device)
Data Points After Removing 0's and Other Abnormal Data from Criterion Device Data
35,774 (260 lines removed)

Documentation of the data processing and data removal steps taken.

Data Analysis

Validation measures were obtained by comparing the results of both trials to the criterion measure at each second. The data was then stratified into five HR phases based on the average age of the participants (see table 4). Validity was determined for each analysis via multiple statistical tests: 1. Error analysis, mean absolute percentage errors (MAPE), mean absolute error (MAE), and mean error (ME), and 2. Correlation analysis, Lin's concordance correlation coefficient (CCC) and Pearson's correlation coefficient (r). Thresholds for validity were predetermined and a MAPE of <10% and a CCC value of >0.7 would result in a valid classification. A device had to satisfy thresholds for both statistical tests to be considered valid. All statistical analyses were performed using Google Sheets (Google LLC, Mountain View CA, USA) and SPSS (Version 24.0, International Business Machines Corp. [IBM], Armonk, NY, USA). Any values registered as a HR of "0" were not factored into the averages.

Table 4. HR Zones

HR Zones	% of MHR	Bottom HR Based on Average Age of Participants	Top HR Based on Average Age of Participants
Zone 1	50-60	97	115
Zone 2	60-70	116	135
Zone 3	70-80	136	154
Zone 4	80-90	155	174
Zone 5	90-100	175	>175

HR zones used for the stratification of the HR data based on the average age of all participants included in the study (n = 20, mean = 26 years).

Reliability was determined via two statistical tests: 1. Intra-class correlation coefficient (ICC) and 2. Coefficient of variation (CV). The predetermined reliability threshold was set at an ICC of >0.7 and a $CV<10\%$ would result in a reliable classification for that device. A device had to satisfy thresholds for both statistical tests to be considered reliable. Reliability was not determined on the stratified data.

The time per trial was determined by calculating the time between the first timestamp of a trial, and the last timestamp. Averages and standard deviation were calculated for the data, and a one-tailed, paired t-test was performed on the mean trial times, and the coefficient of determination (r^2) was calculated for each device. Demographic data was also collected, and averages and standard deviations were calculated.

Results

Time and Heart Rate Data

Of the 16 participants (32 trials) with available data, the average elapsed time for trial 1 was 20.29±6.49 minutes (all values given as mean±SD), which was 1.37 minutes slower than trial 2, which had an average elapsed time of 18.92±5.69 minutes (see table 5). However, the t-test revealed no differences between activity time ($p = 0.07$). The maximum elapsed time for all participants on a single trial was 34.67 minutes, with the shortest lasting 9.90 minutes. The average HR for trial 1 was 159.63±11.53 bpm, 2.24 bpm lower than the trial 2 average of 161.87±11.08 bpm. The t-test showed a significant difference in average HR between trials ($p = 0.018$).

Table 5. Time and Heart Rate Data by Trial

	Trial 1	Trial 2	Average Trial	Combined Trial
Average Time (min)	20.29	18.92	19.61	39.21
Standard Deviation (min)	6.49	5.69	5.85	11.70
Minimum Time Elapsed (min)	11.60	9.90	10.75	21.50
Maximum Time Elapsed (min)	34.67	30.78	31.82	63.65
P-Value From Time Trial T-Test	0.07			
Average Heart Rate (bpm)	159.63	161.87	160.57	
Standard Deviation (bpm)	11.53	11.08	11.16	
P-Value From Avg. HR T-Test	0.018*			

Time and average HR data by trial with accompanying one-tailed, paired t-tests for all participants that data analysis was able to be completed on (n=16, 32 trials). Significance was set at an alpha of 0.05. * indicates statistically significant results.

Validity Measures

Validity measures for the combined data can be found in table 6, while the validity measures for each stratified HR phase are presented in tables 7 - 11. The Suunto Spartan Sport Watch was the only watch to be found valid, according to our pre-establish validity criteria, for the overall data comparisons and the stratified data comparisons. The Rhythm+ and fenix 6 did have acceptable MAPE values in the stratified data comparison for HR zone 1, 2, and 3, while the Polar A360 watch demonstrated acceptable MAPE values for zone 1 only. None of the devices except for the Suunto had acceptable correlation values at any point.

Table 6. Validity Measures – Combined Data

	Polar H7 Chest HRM	Suunto Chest HRM	Rhythm+ HR Monitor	fēnix 5x Watch	Polar A360 Watch	Jabra Earbuds
Average (bpm)	161.79	162.11	144.50	143.94	142.14	140.12
Standard Deviation	19.43	19.51	43.62	37.00	30.23	41.15
Total Data Points	35864	35845	34852	34571	33238	7967
MAPE		0.66%	10.90%	11.12%	13.20%	26.56%
Mean Error		0.32	-17.56	-17.66	-19.59	-23.81
Mean Absolute Error		1.03	18.32	18.60	21.75	43.62
Pearson Correlation		0.99	0.29	0.31	0.41	-0.32
Lin's Concordance		0.99	0.19	0.22	0.29	-0.20
r^2		0.98	0.09	0.10	0.17	0.10

Validity measures for all data and all participants that data analysis was able to be completed on (n = 16, 32 trials). All comparisons were made against the Polar H7 HRM that was used as the criterion.

Table 7. Validity Measures – HR Zone 1

	Polar H7 Chest HRM	Suunto Chest HRM	Rhythm+ HR Monitor	fēnix 5x Watch	Polar A360 Watch	Jabra Earbuds
Average (bpm)	108.74	109.33	100.80	99.64	99.85	161.83
Standard Deviation	5.11	5.77	36.65	15.34	12.89	36.81
Total Data Points	732	732	732	698	567	131
MAPE		1.71%	8.05%	9.99%	9.63%	51.43%
Mean Absolute Error		1.84	8.76	10.92	10.50	56.05
Mean Error		0.58	-7.63	-9.39	-9.38	52.40
Pearson Correlation		0.86	-0.04	0.25	0.42	-0.05
Lin's Concordance		0.85	-0.01	0.11	0.20	0.00

Validity measures for HR zone 1 (97 - 115 bpm, as measured by criterion device) for all participants that data analysis was able to be completed on (n = 16, 32 trials). All comparisons were made against the Polar H7 HRM that was used as the criterion.

Table 8. Validity Measures – HR Zone 2

	Polar H7 Chest HRM	Suunto Chest HRM	Rhythm+ HR Monitor	fēnix 5x Watch	Polar A360 Watch	Jabra Earbuds
Average (bpm)	127.60	127.86	119.74	119.45	120.01	153.85
Standard Deviation	5.53	6.27	31.29	19.67	16.45	26.58
Total Data Points	2607	2604	2607	2582	2532	411
MAPE		1.08%	7.35%	7.72%	10.02%	26.09%
Mean Absolute Error		1.37	9.40	9.85	12.83	33.43
Mean Error		0.27	-7.89	-8.13	-7.65	25.01
Pearson Correlation		0.86	0.16	0.27	0.34	0.15
Lin's Concordance		0.86	0.05	0.12	0.17	0.03

Validity measures for HR zone 2 (116 - 135 bpm, as measured by criterion device) for all participants that data analysis was able to be completed on (n = 16, 32 trials). All comparisons were made against the Polar H7 HRM that was used as the criterion.

Table 9. Validity Measures – HR Zone 3

	Polar H7 Chest HRM	**Suunto Chest HRM**	**Rhythm+ HR Monitor**	**fēnix 5x Watch**	**Polar A360 Watch**	**Jabra Earbuds**
Average (bpm)	146.02	146.26	139.17	138.88	133.91	156.23
Standard Deviation	5.35	5.88	29.00	21.02	20.67	27.18
Total Data Points	7003	6996	7001	6923	6713	1367
MAPE		0.65%	5.69%	6.04%	11.18%	18.38%
Mean Absolute Error		0.94	8.25	8.76	16.44	26.62
Mean Error		0.24	-6.86	-7.09	-12.04	10.87
Pearson Correlation		0.93	0.24	0.31	0.05	-0.07
Lin's Concordance		0.92	0.08	0.13	0.02	-0.02

Validity measures for HR zone 3 (136 - 154 bpm, as measured by criterion device) for all participants that data analysis was able to be completed on (n = 16, 32 trials). All comparisons were made against the Polar H7 HRM that was used as the criterion.

Table 10. Validity Measures – HR Zone 4

	Polar H7 Chest HRM	Suunto Chest HRM	Rhythm+ HR Monitor	fēnix 5x Watch	Polar A360 Watch	Jabra Earbuds
Average (bpm)	165.57	165.95	146.59	146.25	144.71	146.46
Standard Deviation	5.69	5.91	43.90	35.71	28.39	42.05
Total Data Points	14521	14512	14515	13952	13149	3357
MAPE		0.66%	11.78%	12.03%	13.55%	21.10%
Mean Absolute Error		1.09	19.72	20.12	22.44	35.31
Mean Error		0.38	-19.04	-19.30	-20.76	-19.61
Pearson Correlation		0.95	0.00	-0.04	0.13	-0.32
Lin's Concordance		0.95	0.00	-0.01	0.03	-0.07

Validity measures for HR zone 4 (155 - 174 bpm, as measured by criterion device) for all participants that data analysis was able to be completed on (n = 16, 32 trials). All comparisons were made against the Polar H7 HRM that was used as the criterion.

Table 11. Validity Measures – HR Zone 5

	Polar H7 Chest HRM	Suunto Chest HRM	Rhythm+ HR Monitor	fēnix 5x Watch	Polar A360 Watch	Jabra Earbuds
Average (bpm)	181.58	181.85	155.54	155.39	154.35	120.45
Standard Deviation	4.47	4.62	47.43	44.70	33.18	40.14
Total Data Points	9764	9764	9760	9266	9179	2394
MAPE		0.45%	14.33%	14.53%	15.27%	34.47%
Mean Absolute Error		0.81	26.20	26.60	27.88	62.62
Mean Error		0.26	-25.97	-26.26	-27.31	-61.68
Pearson Correlation		0.96	-0.15	-0.09	-0.06	0.21
Lin's Concordance		0.96	-0.02	-0.01	-0.01	0.01

Validity measures for HR zone 5 (>175 bpm, as measured by criterion device) for all participants that data analysis was able to be completed on (n = 16, 32 trials). All comparisons were made against the Polar H7 HRM that was used as the criterion.

Reliability Measures

Test-retest reliability of the mountain biking task was determined with 10-min of rest between trials. Reliability statistics are displayed in table 12. No device, including the criterion, returned acceptable reliability measures for the repeated mountain biking task performed by our participants, according to our predetermined thresholds.

Table 12. Reliability Measures

	Polar H7 Chest HRM	Suunto Chest HRM	Rhythm+ HR Monitor	fēnix 5x Watch	Polar A360 Watch	Jabra Earbuds
Intraclass Correlation Coefficient	0.23	0.24	0.11	0.20	0.35	0.32
Coefficient of Variation	8.16%	8.09%	25.73%	19.24%	12.96%	19.25%

Reliability measures for combined data (n=16).

Data Characterization

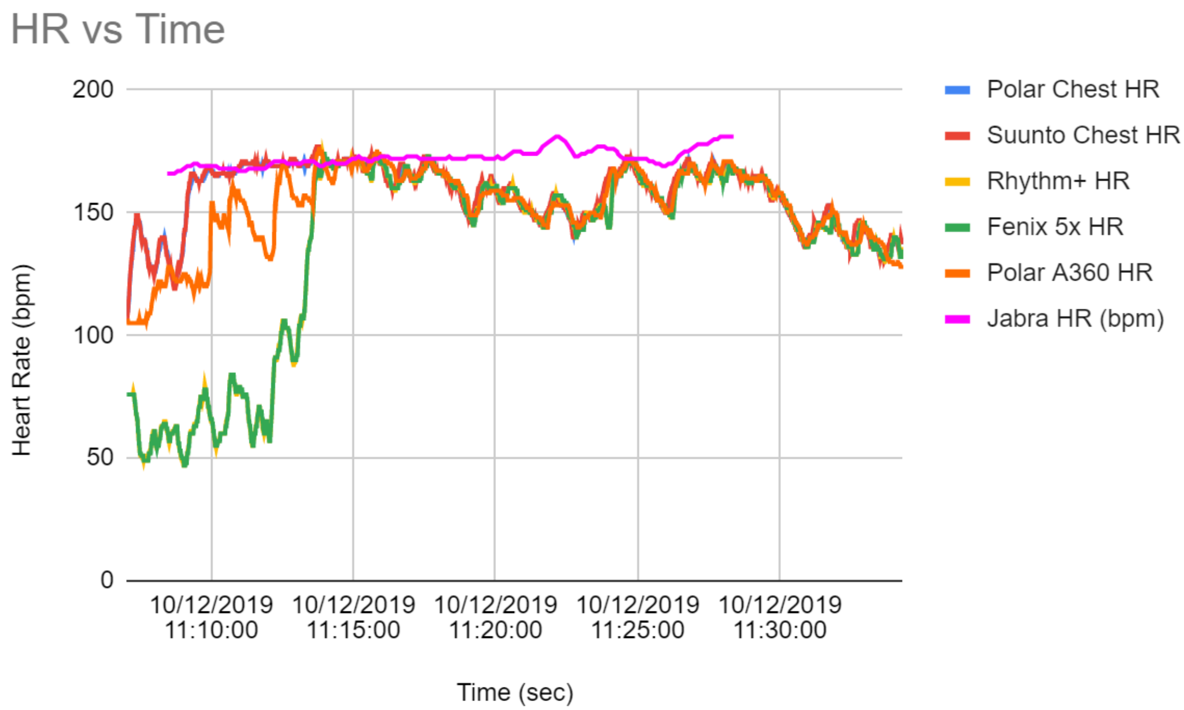
We have also included a data characterization table and a sample graph of a single participant trial and HR output by all devices over time for the convenience of the reader (see table 13 and figure 2). The device that had the greatest data availability, (measured as a percentage of available data points compared to the criterion) in descending order, was the Suunto (99.95%), Rhythm+ (97.17%), fenix 6 (96.44%), Polar A360 (92.66%), and finally the Jabra (22.27%).

Table 13. Data Characterization

	Polar H7 Chest HRM	Suunto Chest HRM	Rhythm+ HR Monitor	fēnix 5x Watch	Polar A360 Watch	Jabra Earbuds
Total 0's	0	0	999	0	0	0
Total Null Values	0	19	13	38	42	27807
Total "-"	0	0	0	1235	2584	0
Summed 0, Null, and “-“ Values	0	19	1012	1273	2626	27807
Total Data Points in Dataset	35774	35755	34762	34501	33148	7967
Data Availability (Percent of Criterion)		99.95%	97.17%	96.44%	92.66%	22.27%

Breakdown of the total number of non-normal values, total data points, and data availability by device (n=16).

Figure 2. Representative graph of a single participant HR outputs from all devices, second by second.



Discussion

The purpose of this study was to determine the validity and reliability of several HR monitors during mountain biking. We hypothesized that all devices would be considered valid and reliable during bouts of mountain biking. Our findings reveal that only the Suunto Spartan Sport watch with accompanying chest strap HRM displayed acceptable overall agreement with the criterion measure. Our study methodology could not properly determine reliability of the devices as time/intensity was not properly controlled for. Thus, we make no conclusion as to the reliability status of the devices but have included the data as a reference.

Heart rate is an important physiological variable, allowing athletes and exercise scientists the ability to measure and track intensity. It is uniquely valuable for pacing, as it can be used independent of the course. Rather than a pace given in terms of min/mi (or similar units) that will change depending on the grade or altitude of the course. Pacing according to HR allows the athletes to maintain a pace at a cardiovascular intensity that is sustainable for them *(28)*. Having an accurate HR measurement is important for mountain biking as it contains many hills and altitude changes. It can also be used for determining overall intensity or zones of the ride for training purposes. Therefore, the data produced by the current study will be valuable for any mountain bikers, coaches, researchers, etc. who want to use HR for race, training, or other purposes.

Sensor Technology Validity and Reliability

The devices used in this study utilize two different types of technology to measure HR, photoplethysmography (PPG) and electrocardiography (ECG). Both technologies have been around for decades and have been important innovations for biosensors, fitness trackers, and wearable technology. Both types of technology have been investigated to determine their validity and reliability during exercise. And while ECG technology continues to out-perform PPG technology, the rapid rise in popularity of PPG devices warrants a more in-depth look at the current state of validity and reliability, possible advantages or disadvantages, and appropriate use-cases for each technology.

The Polar H7 device (criterion) and the Suunto Chest HRM both utilize ECG technology, which measures the electrical signals of the heart. Due to the nature of the technology, these sensors must be worn on the chest, and are often used as an accessory device, paired with a watch or similar device. Wireless ECG monitors have existed since the early 1980's *(29)*, and the technology has been shown to have high agreement with 2-12 medical grade, ambulatory ECGs in a variety of different exercise modalities and intensities *(30-38)*. They have clearly shown themselves to be capable criterion devices when HR is the level of resolution needed, such as in the current study and in many other validation studies. The present investigation found that the Suunto could be considered for a criterion device as the HRM performed well across all intensities, being valid in all five HR zones and overall, in the never-before-examined task of mountain biking. Ironically, these ECG devices had already proved themselves to be valid prior to the emergence of newer wearable technology, and thus the literature surrounding the wireless ECG devices compared to the newer PPG devices is significantly less, even though they are the more robust and accurate devices.

All devices used in the present study except for the Suunto and the Polar H7 use PPG sensor technology, which uses light-based optical sensors to determine the rate of blood flow, and thereby HR. PPG technology has been around since the 1930's and has been integrated into modern fitness-based wearable devices almost as soon as they were developed *(39)*. Unlike the wireless chest based HRMs that utilize ECG technology, PPG technology can be placed virtually anywhere on the body, though the most common is the wrist, forearm, or bicep, with other devices being placed on/in the ear, head, hands, etc. *(17, 40, 41)*. The current study utilized multiple locations on the body to place PPG devices, including both wrists, the forearm, and in the ear. This allows for greater resolution as to how the location and the means of attachment of the device impacts accuracy.

The accuracy of the PPG devices has been studied in a range of exercise modalities and intensities, similar to wireless ECG devices *(42, 43)*. These devices generally have acceptable agreement at rest *(40, 44, 45)* and low intensity exercise *(40, 41, 44-47)*, but tend to decrease in accuracy and performance at higher intensities *(41, 44, 45, 48, 49)*. The exercise modality can also influence the performance of the device greatly *(44, 45, 48-52)*, as the PPG sensors are more susceptible to motion artifacts during movement when measuring the blood flow via the optical sensors than ECG sensors *(53, 54)*. PPG devices have been tested in a range of modalities, including rest *(44, 45, 48, 50)*, walking *(44-46, 48, 49)*, running *(17, 41, 44, 45, 48-50, 52)*, cycling *(44, 45)*, yoga *(47)*, resistance training *(44, 48, 50, 52)* and many more. These findings elicit mixed results for the performance of PPG sensors in measuring HR. It appears certain brands tend to do better than others, and devices at higher price-points tend to do better as well *(55)* likely due to the use of higher quality sensors. As evidenced in the present study and others, the mechanics of securing the device to the body will have an important influence on the stability, and therefore validity of the device *(49, 56)*. Devices that are secured via elastic bands have improved mechanical optimization and tend to do better, especially during high intensity exercise and exercise modalities that involve lots of movement. This is most likely due to the improved mechanical optimization that reduces motion artifacts that limit the performance of the PPG devices *(54)*. While some remedies to the challenges of reading HR through PPG sensors have been suggested *(57)*, it appears that until we can develop or utilize better sensors, mechanical optimization, or algorithms, these devices will continue to be outperformed by ECG monitors.

Some of these devices have been evaluated for reliability. Although, as has been mentioned by multiple previous authors, reliability is an important yet often overlooked aspect when determining the usefulness of these devices *(11, 50)*. Wireless ECG devices have been tested for reliability in a number of studies and has consistently produced acceptable reliability measures *(58-60)*. PPG devices have also been studied for reliability but have mixed results *(61-63)*.

Reliability analysis was performed on the devices utilized in the current study, comparing the device against itself, between trials, using both ICC and CV. We had pre-established criteria for a device to be classified as reliable (ICC>0.7, CV <10%) that no devices achieved, even the criterion. This is most likely due to the participants completing the course faster in the second trial as we did not control for speed/intensity. Although the mean differences between the trial times are not statistically significant (p=0.07) there was a significant difference in average HR between trials (p=0.018). The difference between trials is different enough that they most likely played a role in the low reliability measures. There was also, likely, a learning curve that we did not account for between trials. As we recruited mainly novice mountain bikers, they would have learned how to mountain bike during the first trial, which may have influenced the reliability data. Therefore, if any researchers in the future would like to determine reliability of any wearable devices using similar methods, we encourage the use of a familiarization trial as well as measures to control for intensity/speed. As we did not, we have included the results but will not discuss them further.

In terms of advantages, the Suunto and other wireless ECG monitors have the clear advantage of producing more accurate HR measurements. This extends to accuracy across exercise modalities and intensities. As the ECG technology reads the electrical signals of the heart, it is limited to chest-based monitors. This may be a disadvantage in certain circumstances where the lack of location placement options may influence comfort and compliance with the user. Additionally, wireless ECG sensors are often used as an accessory device to complement the fitness watch or other wearable device, this means that it will likely be more expensive for the user and more work to use both devices, thus leading to lower utilization and compliance. This inconvenience in the need to use multiple devices, and decreased comfort level when compared to PPG-based HR monitors are potential disadvantages athletes, coaches, researchers and others should be aware of when deciding which devices to use.

The PPG sensors in wearable technology can be small and placed virtually anywhere on the body. This represents a major advantage of PPG sensors. They are often incorporated into other devices, such as smart watches, earbuds, phones, etc. that improve compliance. However, as has been shown previously, they have many limitations as to their potential use-cases. Accuracy of PPG sensors is not sufficient for many exercise modalities, and during high intensity exercise the accuracy tends to fall as well. This represents a major disadvantage of PPG sensors, as accuracy is likely the most important factor to consider when choosing a device. If the participant is mountain biking, no PPG monitor tested would be an appropriate choice, as none were classified as valid during mountain biking. Thus, when identifying which HRM to use, the user should consider a number of variables, including body placement, exercise intensity, exercise modality, comfort, cost, required accuracy (and therefore thresholds of validity), and perhaps others to identify which device would be most appropriate for the specific situation.

Measuring and Determining Validity

There are many aspects that a person seeking to use any of these devices to measure HR should consider. However, as suggested earlier, the required accuracy of the device is a crucial factor in the determination of which device to use and is dependent on the proposed use-case. Depending on the potential use-case of the device, the user may require differing levels of accuracy to measure HR. A recreational athlete may need less accuracy than a professional athlete, who may need even less than a researcher. Distinguishing between valid devices and non-valid devices may not provide enough resolution for certain cases, as there are no set validity thresholds. In fact, currently, there is no consensus upon criteria to *measure* accuracy and validity, and accepted thresholds to *determine* validity have even less consensus. While some analytical techniques have been proposed, and common tests have begun to emerge *(11, 64)*, there is a need to standardize validity thresholds for these devices. There will likely need to be multiple thresholds for differing use cases (recreation, athletics, research, etc.). Afterall, if the foundation of validity and reliability studies in the field of wearable technology is to be able to make a determination of whether a device is, in fact, valid, then without the establishment of widely accepted thresholds, the question of validity will remain largely unanswered for these devices. We have used the relatively liberal thresholds of a MAPE<10% and CCC>0.7 for the current study, but as has been established, this is not a universally agreed upon threshold for validity *(45, 51)*.

Limitations

Some of the limitations to the current study have already been discussed, such as a failure to properly control for time/intensity between trials, rendering our analysis of reliability faulty. As stated earlier, if researchers would like to test for reliability, means to control for time and intensity between trials should be enacted to allow for a proper comparison. There is a device limitation in the current study as well. While the Polar H7 HR monitor and similar wireless chest-based ECG HR monitors have been validated previously, our specific device used by the participants had not undergone any validation testing, and we rely on the quality control of Polar Electro Inc. to consistently produce properly working devices. However, as the Suunto and Polar HR monitors had such high agreement, the risk of the manufacture defect occurring in our device is low. Also, while not strictly a limitation, caution when applying this study to newer technology should be considered. As these devices are now many years old, they do not represent any possible advancements made in PPG technology and validity cannot be assumed across differing models and devices. Finally, there may be a possible limitation in the study methodology pertaining to the ability of the PPG devices in reading the HR in a timely manner (compared to the ECG devices). As the ECG devices read the electrical signals of the heart, there is no “lag” in the reading of heart rate for those devices. However, there may be a lag in the PPG devices compared to the ECG, as the change in fluid velocity within the vascular system may take a bit to register by the PPG sensors. A potential lag of even a few seconds could be enough to significantly alter the validity status of the PPG devices when comparing to an ECG criterion device, as could be the case in the current investigation.

Conclusion

This study assessed the validity and reliability of several HR monitors during mountain biking. Participants were asked to wear six devices (one criterion, five test devices) and perform two trials of mountain biking. Due to time trial and average HR differences, reliability analysis was performed, and the results are included above, but no conclusions were not drawn due to limitations in controlling for performance of the repeated task. There was only one device that met the pre-established validity criteria, which was the Suunto Spartan Sport Watch with Chest HRM. This device may be considered valid in producing measures of HR while mountain biking. Forearm-based devices (and likely bicep-based devices) secured through elastic straps would be a better alternative to wrist-based devices if chest monitors are not available, though they were not considered valid, according to the data obtained in this investigation. Therefore, if a person would like to track their HR during mountain biking, for pacing, training, or other reasons, the devices best able to produce valid results are chest-based, wireless ECG monitors, secured by elastic straps to minimize the movement of the device, such as the Suunto chest-based HRM.

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Curriculum Vitae

Bryson Carrier
brysoncarrier@gmail.com
Henderson, NV

Education

University of Nevada, Las Vegas, Las Vegas NV

- Degree: Master of Science, Kinesiology
    - Concentration: Exercise Physiology
- Expected Graduation Date: May 2021
- GPA: 4.0

Utah Valley University, Orem UT

- Degree: Bachelor of Science, Biology
- Graduation Date: Aug. 11, 2017
- GPA: 3.75

Standardized Tests

Graduate Record Examination (GRE)

- Cumulative Score: 315.5 (Verbal, 157; Quantitative, 155; Analytical Writing, 3.5)
- Percentile: Verbal, 76^{th}; Quantitative, 58^{th}, Analytical Writing, 41^{st}
- Date Taken: Dec. 21, 2018

Major Field Test (MFT) - Biology

- Score: 168
- Percentile: 85^{th}
- Date Taken: May 2, 2017

Relevant Experience

University of Nevada, Las Vegas – Multiple Dates and Roles

- **Graduate Student (Master's) -** Aug. 2019 to Present
  - Master's student, studying Kinesiology with an emphasis in exercise physiology.
- **Student Researcher** - Aug. 2019 to Present
  - Researcher in Exercise Physiology lab, studying wearable technology, sport performance, sport nutrition, and others under Dr. James Navalta.
- **Instructor / Graduate Assistant** - Aug. 2019 to Present
  - Instructor teaching exercise physiology labs (for graduate assistantship), as well as indoor soccer and spin courses (as adjunct / part-time instructor).

International Journal of Exercise Science - Dec. 2019 to Present

Student Reviewer. Have reviewed manuscripts on a range of exercise science topics, including exercise physiology, wearable technology, cycling, running, sport performance, etc.

Utah Valley University - Multiple Dates and Roles

- **Adjunct Faculty Member** - Aug. 2018 to Jul. 2019
  - Adjunct faculty member in the Biology department. Taught introductory biology labs for life science and non-science majors.
- **Research Assistant** - Jan. 2018 to Jul. 2019
  - Research assistant in Biomechanics and Human Performance Lab. Tasks included collecting kinematic, EMG, metabolic, physiologic, and other types of data for multiple research studies.
- **Research Assistant** - Nov. 2018 to Jul. 2019
  - Research assistant in Brooks Microbiology Lab. Researched microbial community of indoor rock-climbing walls. Tasks included PCR, analyzing

sequenced genetic data, DNA extraction, electrophoresis, PCR cleaning, applying source tracking techniques to samples and culturing bacteria.

- **Research Assistant** - Jun. 2015 to Jun. 2017
  - Research assistant in Ogden Bioinformatics Lab. Researched evolution of Mayflies. Tasks included PCR, analyzing sequenced genetic data, DNA extraction, electrophoresis, PCR cleaning, and constructing phylogenetic trees.
- **Teacher's Assistant** - Jan. 2016 to May 2016
  - Teacher's Assistant for introductory biology class. Tasks included multiple weekly review sessions, one-on-one tutoring, grading, and weekly coordination with professors.

Grow.com – Feb. 2018 to Jun. 2018

Data Analyst / Account Manager for a business intelligence company. Tasks included reviewing data, writing SQL, and building metrics relevant to the customer and the company.

Free Health Clinic – Apr. 2016 to Jun. 2017

Volunteer Phlebotomy Technician for Free Health Clinic. Responsibilities included drawing blood from arm or hand for a range of tests determined by physicians.

American Fork Physical Therapy – Mar. 2016 to Nov. 2016; May 2017 to Aug. 2017

Physical Therapy Technician. Tasks included helping patients with workouts for strength, range of motion, coordination and set-up with different modalities and equipment.

Teaching Experience

University of Nevada, Las Vegas – Aug. 2019 to Present

- Courses Taught:
  - KIN 391 - Exercise physiology lab

- PEX 124 - Indoor soccer
- PEX 154 - Indoor cycling

Utah Valley University – Aug. 2018 to Jul. 2019

- Courses Taught:
  - BIOL 1015 – Biology lab for non-science majors
  - BIOL 1615 – Biology lab for life science majors

Manuscripts

Published Manuscripts

1. **Carrier, B.**; Barrios, B.; Jolley, B.D.; Navalta, J.W. Validity and Reliability of Physiological Data in Applied Settings Measured by Wearable Technology: A Rapid Systematic Review. Technologies 2020, 8, 70. https://doi.org/10.3390/technologies8040070
2. **Carrier, Bryson**, Creer, Andrew, Williams, Lauren R., Holmes, Timothy M., Jolley, Brayden D., Dahl, Siri, Weber, Elizabeth, & Standifird. Tyler. (2020). Validation of Garmin Fenix 3 HR Fitness Tracker Biomechanics and Metabolics (VO2max). Journal for the Measurement of Physical Behaviour. Advance online publication. https://doi.org/10.1123/jmpb.2019-0066.
3. Barrios, Brenna; **Carrier, Bryson**; Jolley, Brayden D.; Davis, Dustin W.; Sertic, Jacquelyn; and Navalta, James W. (2020) "Establishing a Methodology for Conducting a Rapid Review on Wearable Technology Reliability and Validity in Applied Settings" Topics in Exercise Science and Kinesiology: Vol. 1 : Iss. 2 , Article 8. https://digitalscholarship.unlv.edu/scholarship_kin/vol1/iss2/8
4. Salatto, R W.; Davis, Dustin W.; **Carrier, Bryson**; Barrios, Brenna; Sertic, Jacquelyn; Cater, Peyton; and Navalta, James W. (2020) "Efficient Method of Delivery for Powdered Supplement or Placebo for an Outdoor Exercise Investigation" *Scholarship in Kinesiology*: Vol. 1 : Iss. 2 , Article 5. https://digitalscholarship.unlv.edu/scholarship_kin/vol1/iss2/5

Manuscripts Submitted (in-review)

1. Navalta, James; Davis, Dustin; **Carrier, Bryson**; Sertic, Jacquelyn; Cater, Peyton, (Jul. 2020) "Teaching Applied Exercise Physiology Using a Prototype Energy Expenditure Measurement Device". Submitted to *Interdisciplinary Journal of Problem-Based Learning.*

Scientific Presentations

Oral Presentations

1. Symposium: Wearable Activity Monitors. Introduction of student presenters, Navalta, J.W.; The evolution of wearable devices, Salatto, R.W.; The current state of technology devices in applied settings, Barrios, B.; The needed considerations in current testing models, Jolley, B.D.; The future of wearable exercise testing, **Carrier, B.**, Virtual Annual Meeting of the *Southwest American College of Sports Medicine*, 2020.
2. **Carrier, B.**; Salatto, R.W.; Manning, J.W.; Barrios, B.; Sertic, J.V.L.; Davis, D.W.; Cater, P.C.; McGinnis, G.; DeBeliso, M.; Navalta, J.W., "Does Acute Beta-Alanine Supplementation Improve Performance, Rating of Perceived Exertion and Heart Rate During Hiking?", *American College of Sports Medicine*, May 2020, San Francisco, CA, USA. Presented as a thematic poster presentation.

Poster Presentations

1. **Carrier, Bryson**; Cruz, Kyle; Farmer, Heather; Navalta, James, "Validation of the Lactate Threshold Estimate from the Garmin fenix 6 Fitness Tracker", *University of Nevada, Las Vegas Annual Graduate and Professional Student Research Forum*. April, 2021, Las Vegas, NV, USA.

2. **Carrier, B.**; Trainor, T.; Jolley, B.W.; Navalta, J.W.; Creer, A., “Validation of the Humon Hex Lactate Threshold Estimate”, *Southwest American College of Sports Medicine*, Oct. 2019, Costa Mesa, CA, USA.
3. **Carrier, B.**; Holmes, T.; Williams, L.; Dahl, S.; Weber, L.; Creer, A.; Standifird, T., “Validation of Garmin Fitness Tracker Biomechanics”, *American College of Sports Medicine*, May 2019, Orlando, FL, USA.
4. **Carrier, B.**; Richards, S.; Hancock, C.; Brooks, L., “Who Brought the Microbes? Investigating the source of fecal veneer on rock climbing holds”, *Intermountain American Society of Microbiologists*, Apr. 2019, Provo, UT, USA.
5. **Carrier, B.**; Holmes, T.; Williams, L.; Dahl, S.; Weber, L.; Creer, A.; Standifird, T., “Validation of Garmin Fitness Tracker Biomechanics”, *Southwestern American College of Sports Medicine*, Oct. 2018, Costa Mesa, CA, USA.
6. **Carrier, B.**; Ferguson, D.; Ogden T.H., “Molecular Phylogeny of Baetidae (Ephemeroptera)”, *Evolution 2017*, June 2017, Portland, OR, USA.
7. **Carrier, B.**; Ferguson, D.; Ogden T.H., “Molecular Phylogeny of Baetidae (Ephemeroptera)”, *Utah Conference for Undergraduate Research*. Feb. 2017, Orem, UT, USA.
8. **Carrier, B.**; Ogden T.H., “Phylogenetic Relationships of Mayfly Family Baetidae (Ephemeroptera)”, *Utah Conference for Undergraduate Research*. Feb. 2016, Salt Lake City, UT, USA.

Abstracts

Peer Reviewed Abstracts

1. **Carrier, Bryson**; Cruz, Kyle; Farmer, Heather; Navalta, James, “Validation of the Lactate Threshold Estimate from the Garmin fenix 6 Fitness Tracker”, American College of Sports Medicine, Jun. 2021, Washington D.C., USA.
2. Cruz, Kyle; **Carrier, Bryson**; Farmer, Heather; Navalta, James, “The Validity of VO2 Max: Treadmill GXT and Wearable Technology”, American College of Sports Medicine, Jun. 2021, Washington D.C., USA.

3. **Carrier, Bryson**; Cruz, Kyle; Farmer, Heather; Navalta, James, "Validation of the Lactate Threshold Estimate from the Garmin fenix 6 Fitness Tracker", *University of Nevada, Las Vegas Annual Graduate and Professional Student Research Forum*. April, 2021, Las Vegas, NV, USA.
4. Cruz, Kyle; **Carrier, Bryson**; Farmer, Heather; Navalta, James, "The Validity of VO2 Max: Treadmill GXT and Wearable Technology", *University of Nevada, Las Vegas Annual Graduate and Professional Student Research Forum*. April, 2021, Las Vegas, NV, USA.
5. Kyle Cruz; RW Salatto; Dustin W. Davis; **Bryson Carrier**; Brenna Barrios; Peyton Cater; Heather Farmer; James W. Navalta, "Evaluation of Rating of Perceived Exertion During Mountain Biking", *Southwest American College of Sports Medicine*, Oct. 2020, Costa Mesa, CA, USA.
6. Heather Farmer; Heather Farmer, RW Salatto, Dustin Davis, **Bryson Carrier**, Brenna Barrios, Peyton Cater, Kyle Cruz, James Navalta, FACSM, "Felt Arousal Scale is Not Reliable for Use in Repeated Mountain Biking Trial Application", *Southwest American College of Sports Medicine*, Oct. 2020, Costa Mesa, CA, USA.
7. **Carrier, B.**; Salatto, R.W.; Manning, J.W.; Barrios, B.; Sertic, J.V.L.; Davis, D.W.; Cater, P.C.; McGinnis, G.; DeBeliso, M.; Navalta, J.W., "Does Acute Beta-Alanine Supplementation Improve Performance, Rating of Perceived Exertion and Heart Rate During Hiking?", *American College of Sports Medicine*, May 2020, San Francisco, CA, USA.
8. Barrios, B.; **Carrier, B.**; Cater, P.C.; Sertic, J.V.L.; Salatto, R.W.; Navalta, J.W., "Validation of Heart Rate Monitoring of Fenix 5 During Mountain Biking", *American College of Sports Medicine*, May 2020, San Francisco, CA, USA.
9. Sertic, J.V.L.; **Carrier, B.**; Cater, P. C.; Barrios, B.; Salatto, R. W.; Navalta, J. W., "Validation of Two Wearable Chest Straps for Heart Rate Monitoring During Mountain Biking", *American College of Sports Medicine*, May 2020, San Francisco, CA, USA.
10. Salatto, R.W.; Navalta, J.W.; Montes, J.; Bodell, N.; **Carrier, B.**; Sertic, J.V.L; Barrios, B.; Cater, P.C.; Davis, D.W.; Manning, J.W.; DeBeliso, M., "Evaluating the Validity of

Heart Rate Measured by the Suunto Spartan Sport Watch During Trail Running", *American College of Sports Medicine*, May 2020, San Francisco, CA, USA.

11. Navalta, J.W.; McGinnis, G.R.; Manning, J.W.; Salatto, R.W.; **Carrier, B.**; Davis, D.W.; Sertic, J.V.L.; Cater, P.C.; Barrios, B.; Malek, E.M.; Reynolds, C.K.; DeBeliso, M., "Acute Beta-Alanine Supplementation and Pain Perception Before and After Hiking", *American College of Sports Medicine*, May 2020, San Francisco, CA, USA.
12. Trainor, T.; **Carrier, B.**; Jolley, B.W.; Creer, A.; "Validation of the Humon Hex Lactate Threshold Estimate", *American College of Sports Medicine*, May 2020, San Francisco, CA, USA.
13. Standifird, T.; Williams, L.; **Carrier, B.**; Creer, A., "Differences Between Predicted And Measured $V0_2$ During Level And Uphill Walking", *American College of Sports Medicine*, May 2020, San Francisco, CA, USA.
14. **Carrier, B.**; Trainor, T.; Jolley, B.W.; Navalta, J.W.; Creer, A., "Validation of the Humon Hex Lactate Threshold Estimate", *Southwest American College of Sports Medicine*, Oct. 2019, Costa Mesa, CA, USA.
15. Barrios, B.; Sertic, J.V.L.; Cater, P.C.; Davis, D.W.; **Carrier, B.**; Salatto, R.W.; Montes, J.; Bodell, N.; Manning, J.W.; DeBeliso, M.; Navalta, J.W., "Evaluating the Validity of Heart Rate Measured by the Jabra Elite During Trail Running", *Southwest American College of Sports Medicine*, Oct. 2019, Costa Mesa, CA, USA.
16. Cater, P.C.; Sertic, J.V.L.; Davis, D.W.; Barrios, B.; **Carrier, B.**; Salatto, R.W.; Montes, J.; Bodell, N.; Manning, J.W.; DeBeliso, M.; Navalta, J.W., "Evaluating the Validity of Heart Rate Measured by the Rhythm During Trail Running", *Southwest American College of Sports Medicine*, Oct. 2019, Costa Mesa, CA, USA.
17. Davis, D.W.; Barrios, B.; **Carrier, B.**; Salatto, R.W.; Sertic, J.V.L.; Cater, P.C.; Montes, J.; Bodell, N.; Manning, J.W.; DeBeliso, M.; Navalta, J.W., "Evaluating the Validity of Heart Rate Measured by the Garmin Fenix 5 During Trail Running", *Southwest American College of Sports Medicine*, Oct. 2019, Costa Mesa, CA, USA.
18. Salatto, R.W.; Navalta, J.W.; Montes, J.; Bodell, N.; **Carrier, B.**; Sertic, J.V.L; Barrios, B.; Cater, P.C.; Davis, D.W.; Manning, J.W.; DeBeliso, M., "Evaluating the Validity of

Heart Rate Measured by the Suunto Spartan Sport Watch During Trail Running", *Southwest American College of Sports Medicine*, Oct. 2019, Costa Mesa, CA, USA.

19. Sertic, J.V.L.; Cater, P.C.; Davis, D.W.; Barrios, B.; **Carrier, B.**; Salatto, R.W.; Montes, J.; Bodell, N.; Manning, J.W.; DeBeliso, M.; Navalta, J.W., "Validating the Heart Rate Feature of the Motiv Ring on Outside Graded Terrain", *Southwest American College of Sports Medicine*, Oct. 2019, Costa Mesa, CA, USA.
20. Navalta, J.W.; Salatto, R.W.; Montes, J.; Bodell, N.; **Carrier, B.**; Sertic, J.V.L.; Barrios, B.; Cater, P.; Davis, D.; Manning, J.W.; DeBeliso, M., "Wearable Device Price is Correlated with the Limits of Agreement Range as a Measure of Heart Rate Validity during Trail Running", *Southwest American College of Sports Medicine*, Oct. 2019, Costa Mesa, CA, USA.
21. **Carrier, B.**; Holmes, T.; Williams, L.; Dahl, S.; Weber, L.; Creer, A.; Standifird, T., "Validation of Garmin Fitness Tracker Biomechanics", *American College of Sports Medicine*, May 2019, Orlando, FL, USA.
22. Jolley, B.W.; **Carrier, B.**; Standifird, T.; Creer, A., "Validation of Garmin Fitness Tracker Metabolic Data (VO2max)", *American College of Sports Medicine*, May 2019, Orlando, FL, USA.
23. **Carrier, B.**; Richards, S.; Hancock, C.; Brooks, L., "Who Brought the Microbes? Investigating the source of fecal veneer on rock climbing holds", *Intermountain American Society of Microbiologists*, Apr. 2019, Provo, UT, USA.
24. **Carrier, B.**; Holmes, T.; Williams, L.; Dahl, S.; Weber, L.; Creer, A.; Standifird, T., "Validation of Garmin Fitness Tracker Biomechanics", *Southwestern American College of Sports Medicine*, Oct. 2018, Costa Mesa, CA, USA.
25. **Carrier, B.**; Ferguson, D.; Ogden T.H., "Molecular Phylogeny of Baetidae (Ephemeroptera)", *Evolution 2017*, June 2017, Portland, OR, USA.
26. **Carrier, B.**; Ferguson, D.; Ogden T.H., "Molecular Phylogeny of Baetidae (Ephemeroptera)", *Utah Conference for Undergraduate Research*. Feb. 2017, Orem, UT, USA.

27. **Carrier, B.**; Ogden T.H., "Phylogenetic Relationships of Mayfly Family Baetidae (Ephemeroptera)", *Utah Conference for Undergraduate Research*. Feb. 2016, Salt Lake City, UT, USA.

Master's Thesis

University of Nevada, Las Vegas

- Assessing the Validity and Reliability of Several Heart Rate Monitors in Wearable Technology While Mountain Biking
    - Oral defense to Dr. James Navalta (committee chair), Tedd Girouard, Dr. Graham Mcginnis, and Dr. Benjamin Burroughs (graduate college representative), April 15, 2021.

Undergraduate Senior Thesis

Utah Valley University, Orem UT

- Phylogenetic Analysis of the Baetidae Family
    - Oral defense to Dr. T. Heath Ogden & Dr. James G. Harris, May 4, 2017

Funding

Awarded

- University of Nevada, Las Vegas
    - Kinesiology Department - Mentor Directed Research Award, Dec. 2019, $1,500
    - Graduate & Professional Student Association Research Grant, Nov. 2019, $1040
    - UNLV Access Grant, Aug. 2019, $1000
- Utah Valley University, Orem UT
    - Scholarly Activities Committee Grant, College of Science, Apr. 2019, $4684
    - Scholarly Activities Committee Grant, College of Science, Jan. 2019, $2000
    - Scholarly Activities Committee Grant, College of Science, Nov. 2018, $4000

Applied For

- University of Nevada, Las Vegas
    - Department of Kinesiology and Nutrition Sciences, Graduate Student Research Award, Dec. 2020, $1500
- National Strength and Conditioning Association Foundation Grant
    - Graduate Student Research Grant, Feb. 2020, $15,000
- National Science Foundation (NSF)
    - NSF Graduate Research Fellowship Program (GRFP), Oct. 2019, $138,000
- Utah Valley University, Orem UT
    - Undergraduate Research Scholarly and Creative Activities Grant, Feb. 2017, $3000
    - Undergraduate Research Scholarly and Creative Activities Grant, Oct. 2016, $3000

Certifications

- American Red Cross Adult and Pediatric First Aid/CPR/AED Certification
- Indoor Cycling Instructor Certification
- Collaborative Institutional Training Initiative (CITI) Certification

Fitness & Coaching Experience

University of Nevada, Las Vegas

- Indoor Spin Instructor - Jan. 2020 - Present
- Indoor Soccer Instructor- Aug. 2020 - Present

Momentum Climbing Gym

- Youth Rock Climbing Coach - May 2017 – Aug. 2017

Honors & Awards

Utah Valley University

- Graduated with Distinction (Cum Laude), Aug. 2017
- Dean's List 2014 to 2017

University of Nevada, Las Vegas

- 2nd Place Winner for Poster Presentation Group, GPSA Research Forum, Apr. 2021

Volunteer / Service Experience

- Volunteer Phlebotomist at Volunteer Care Clinic, Apr. 2016 – Jun. 2017
- Committee Chair for Utah Valley University & University of Utah Pre-Health Conference, Sep. 2016 – Jan. 2017
- Special Needs Activity Program Volunteer, Mar. 2016 – Dec. 2016
- Committee Member for Utah Valley University & University of Utah Pre-Health Conference, Sep. 2015 – Jan. 2016
- Special Needs Tutor at Local Elementary School, Aug. 2015 – Mar. 2016