Chapter 5. EXTRAVEHICULAR ACTIVITY METABOLIC RATE MODEL: METABOLIC RATE ESTIMATED FROM HEART RATE

5.1 Summary

In-flight monitoring of crew metabolic rates during extravehicular activity (EVA) provides crucial information in mitigating injury. The purpose of this study was to investigate the relationship of crewmember heart rate (HR) and metabolic rate (MR) during EVA operations to develop a predictive linear model. HR and MR data was collected from 132 EVAs from Shuttle and International Space Station (ISS) missions. MR was collected every 2-min from portable life support system delta oxygen decay, while HR was collected every 20-sec via electrocardiogram. HR was down sampled to every 2-min to match MR during EVA for evaluation. Further, a new metric was observed from direct relations between metabolic rate with HR over EVA time (MR/HR) measured as a BTU/beat. A range of BTU/beat was collected as a conversion scale between MR and HR at different EVA workloads categorized by increased MR. Both HR and MR values were observed to decrease through the duration of EVA. Similarly, HR and MR slopes decreased at start of EVA compared to end of EVA. MR/HR values were used to predict MR from HR over the entire duration of EVA with root mean square error less than 200 BTU/Hr. Additionally, MR was predicted based on HR values during EVA via a calculated simple linear regression. A regression equation was found for each EVA drawing relations between HR and MR (F (2923.84) and $P<0.0001$) with an R^2 value of 0.402. Individual crew regressions improved prediction and R^2 to greater than 0.82. Two models are presented to determine metabolic rate from heart rate during EVA. Results draw correlations for heart rate and metabolic rate fluctuations during EVA for individualized crew predictions during future operations. The linear models correlate to Apollo prediction data during historic EVAs.

5.2 Background

Monitoring crew health during spaceflight missions is important to mitigate injury during exploration operations such as extravehicular activity (EVA). Spaceflight brings with it a host of unforgiving environments. An element of these environments is altered gravitational forces. Prolonged exposure to microgravity produces an array of deconditioned physiologic systems. Among those systems most effected is the cardiovascular system. Gravity greatly impacts cardiovascular regulation during daily activities. Tasks such as running/walking or lifting objects are known to increase heart rate relative to metabolic energy expenditure [203], [204].

During prolonged weightlessness, demands of everyday tasks dramatically change in parallel to the relief of gravitational loading on the cardiovascular system. Baroreflex responses adjust to maintain cardiovascular regulation due to headward fluid shifts [25], [172]. During flight heart rate (HR) has been shown to remain relatively unchanged throughout long-term spaceflight due to a shift in cardiovascular regulation [15], [148]. One study by Norsk et al., observed HR remained unchanged with increasing cardiovascular output, increased vasodilation despite increases in venous return and cardiac output lead to decreases in systemic vascular resistance due to headward fluid shifts, likely responses to mitigate increased blood pressure [148]. Additionally, Fraser et al., had shown that daily HR had not changed during prolonged stays on the ISS including observations during sleeping and exercise [205]. These studies suggest cardiovascular fitness and HR may be preserved through prolonged spaceflight.

Tied to cardiovascular activity is metabolic demand. During EVA, high workloads and prolonged workloads can lead to risks of injury and physiologic strain. Real-time monitoring of metabolic rate is an important factor during EVA for tracking life support consumables, crew member safety, and planning task operations. Ultimately, accurate estimations of metabolic rates in real-time can help determine if a crew member is achieving maximum work rates during short maximum efforts which could cause injury. Further, metabolic rates can give a picture into the physiologic state of the crew member such as metabolic heat generation. Metabolic heat generated by normal activity can be tracked through oxygen consumption. Measuring oxygen consumption is a widely accepted research methodology to determine energy expenditure [206].

Metabolic rates were not directly measured in real-time during early Gemini missions, where it was determined that crew members exhibited higher than expected energy expenditure which stressed the cooling capability of the portable life support system ultimately including evident overheating during EVA [4]. Metabolic rates during these missions were not directly measured but energy expenditure was determined based on workload correlations post flight through HR and respirations rate analysis. During Apollo, three techniques were attempted to monitor real-time metabolic rates through oxygen consumption, liquid cooling garment (LCG) heat balance and through HR estimations [4]–[6].

Oxygen consumption method was estimated through differential pressure decay of the oxygen bottle pressure of the portable life support system. This method experienced noise and included suit leakage which induced error from the oxygen that was not consumed by the crew member. Due to this noise heat balance of the LCG was used through a relation of heat removal and LCG inlet temperature. Similarly, utilizing the current liquid cooling and ventilation garment (LCVG) flow rates, a method comparable to direct calorimetry methods, was shown to be unreliable when used alone to predict metabolic rates [4].

HR correlations to metabolic rate during Apollo were determined through pre-flight exercise and through linear regressions used in-flight. This technique was subjected to noise due to psychophysical responses causing short term elevated heart rate due to the environment. However, HR methodology allows for estimations of metabolic cost and energy expenditure per task during minute-by-minute observations [6], [50]. Because of the uncertainty of all three of these methods, all of them were used simultaneously during Apollo [207]. Current EVA operations use pressure decay of the portable life support system oxygen supply to estimate crew member metabolic rates [208]. Though it is understood that these measurements can induce large errors [4].

Terrestrially, HR and cardiovascular function are highly correlated to energy expenditure. Buresh et al., show that heat production is directly correlated to body size, composition and HR fluctuations during high intensity running [209]. Body size and cardiovascular drift seen during exercise has a profound effect on energy expenditure ultimately affecting heat storage. Increased heat storage can further lead to degradation of physical workload leading to serious injury. Further, predictions of thermal regulation have been investigated by some studies involving soldier and firefighter workloads utilizing HR [210]. Linear regressions have shown to have high confidence in predicting core temperature and thermal regulatory processes as well as metabolic rates [210], [211].

In this paper correlation of heart rates and metabolic rate are drawn and presented from EVAs during shuttle and international space station (ISS) missions. Metrics of a relationship between metabolic rate and HR over time are presented to include conversion factors at various energy expenditure ranges. Further, a linear regression model was developed to predict metabolic rates from heart rates during EVA.

5.3 Methodology

5.3.1 EVA Dataset

The dataset consisted of 140 individual sets of HR and metabolic rate data collected during Shuttle and ISS EVA collected from 2006 to 2015. Metabolic rate was collected every two minutes as a delta decay of oxygen tank pressure of the suit. HR was collected every twenty seconds via electrocardiogram. Data was removed from analysis if the length of EVA was less than five hours and if the signal had more than twenty five percent of loss of signal (LOS) noise. The final number of signals analyzed in this study was 132 individual EVA heart rate and metabolic rate signals.

5.3.2 Heart Rate and Metabolic Rate Calculations

HR and metabolic rate (MR) were investigated to identify if there was cardiovascular or metabolic drift across the EVA time. First, HR was down sampled to every two minutes to correspond to MR sampling. A 10-point moving average was used on both HR and MR values to smooth short-term fluctuation noise [50]. Then HR and MR values were extracted from the EVA signal at various times, Start, 1Hr, 2Hr, 3Hr, 4Hr and End. Values at each time step were used to determine the difference between the starting value of HR and MR to view if there was a drift occurring.

Additionally, a new metric technique was conducted from direct relations between metabolic rate with HR over EVA time (MR/HR). This metric was defined as a BTU/beat and was used to develop scales of energy expenditure across ranges of metabolic rate activity per heartbeat. Further, MR values were separated into bins of metabolic ranges (BTU/hr) <600, 600-800, 800-1000, 1000-1200 and >1200. EVA tasks were not consistent between each individual EVA within the dataset. This is due to the EVAs being conducted over multiple different missions and by different individual crew members. Corresponding HR values were separated into each bin and compared to each other metabolic range to view HR changes due to increasing energy expenditure. HR was predicted using sorted and non-sorted MR/HR values as the generated conversion scale. Additionally, MR was predicted from the MR/HR values to compare with outputs to linear regression relations.

5.3.3 Evaluation and Model Correlations

A simple linear regression model was generated utilizing the EVA dataset developed to observe the responses of metabolic rate from corresponding heart rate values. First a simple linear regression was fit first on a subset of the total number of EVA HR and corresponding MR values as a training set. Then the model was tested against the subsequent testing set of EVA HR and MR data. The training-testing paradigm was split eighty percent as training and twenty percent as testing. As EVA tasks were not constant between all the EVAs in the historic dataset individual regressions were developed as well. To improve predictions, a separate simple linear regression was also calculated using single EVAs for individual responses, training-testing paradigm was split fifty percent of the signal for training and the remaining fifty percent for testing. A subsection of individual EVA was used as a training set and the remaining portion of the EVA was the testing set. Prediction error (RMSE) of < 200 BTU/hr was deemed accurate based on results from previous Apollo HR data [207].

5.3.4 Statistics

Normality was determined using the Shapiro-Wilk test at $\alpha = 0.05$. For normally distributed data, a one-way ANOVA was used to compare HR and MR values at 1Hr, 2Hr, 3Hr, 4Hr and End compared with values at the start of EVA to determine if cardiovascular drift occurred. Similarly, a one-way ANOVA was used to compare HR values in different metabolic ranges to determine fluctuations to increasing energy expenditure. MATLAB 2019a was used for statistic calculations.

Linear regression modeling was created using matlab *fitlm()* function to fit the regression model. The predicted variable of interest was metabolic rate with the independent value being heart rate. A one-way ANOVA of the model components was conducted to determine fit regression equation significance and F-statistics. Additionally, root mean square error (RMSE) was used to determine acceptance of the linear regression model and conversions scale MR/HR metabolic rate predictions [207].

5.4 Results

Both HR and MR values for all EVAs passed the test for normality. General significant decreases of both HR and MR values were observed as the EVA durations progressed compared to the starting values, starting at hour one and in one-hour increments to the end of EVA (Table 1, Figure 1). Further, during increased workloads, HR and MR slopes decreased near the end of EVA compared to starting workload changes. MR/HR metrics were generated to quantify a BTU per beat as a relationship over time. Across EVA, MR/HR metrics did not show trends of cardiovascular or metabolic drift (Table 1). Metabolic rate values and predicted metabolic rate values from MR/HR did not show significant differences ($p>0.23$) (Table 1).

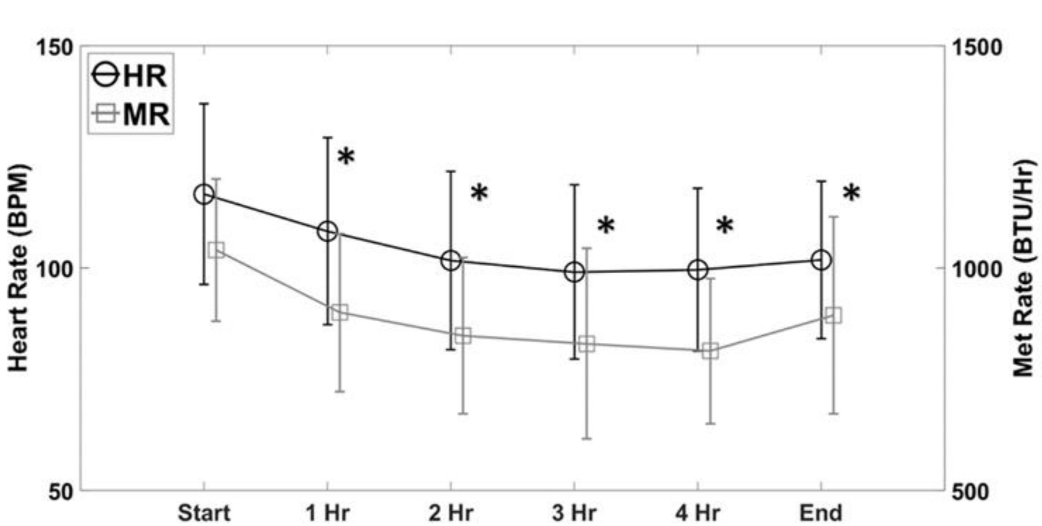

Figure 5.1: Heart rate (HR) and metabolic rate (MR) observations across five hours of operations of 132 EVAs. Both HR and MR values show decreasing trends across the EVA duration suggesting lack of cardiovascular and energy expenditure drift, however, increased linear relations (* designates p<0.05 compared to the starting values).

Table 5.1: EVA observations, predictions including linear regression model F-Test and Coefficient Tests. (* denotes p<0.01 compared to EVA starting values)

EVA INCREMENT TOTALS							
Variable, Unit	**START**	**HOUR 1**	**HOUR 2**	**HOUR 3**	**HOUR 4**	**END**	**ALL**
Metabolic Rate (BTU/hr)	1040.3 ± 159	899.9 * ± 177	847.9 * ± 176	830.0 * ± 214	813.3 * ± 163	893.1 * ± 221	862.9 ± 125
Heart Rate (BPM)	117 ± 20	108 * ± 21	102 * ± 20	99 * ± 19	100 * ± 18	101 * ± 18	103 ± 17
MR/HR (BTU/Beat)	0.153 ± 0.03	0.141 ± 0.02	0.142 ± 0.03	0.142 ± 0.03	0.139 ± 0.03	0.149 ± 0.04	0.142 ± 0.03
Total Generated Heat (BTU)	3111 ± 675	28830 ± 3932	108706 ± 14571	238319 ± 33242	416875 ± 60803	831401 ± 126547	-
MR Predicted From MR/HR (BTU/hr)	1065.9 ± 185	911.3 * ± 177	861.1 * ± 170	834.5 * ± 165	815.3 * ± 150	818.6 * ± 142	873.8 ± 151
Predicted Generated Heat (BTU)	3252 ± 561	29545 ± 5170	110894 ± 19384	242283 ± 42515	422607 ± 73674	783483 ± 138069	-

SIMPLE REGRESSION FROM HEART RATE

F-TEST				
VARIABLE, UNIT	**numDF**	**denDF**	**F-VALUE**	**P-VALUE**
Metabolic Rate (BTU/hr)	1	5434	2923.84	<0.0001

COEFFICIENT TESTS						
VARIABLE, UNIT	**TEST**	**COEFFICIENT**	**SE**	**DF**	**T-VALUE**	**P-VALUE**
Metabolic Rate (BTU/hr)	Intercept	284.55	10.94	5434	26.02	<0.0001
	Slope	5.984	0.111	5434	54.07	<0.0001

MR/HR metrics did not show decreasing or increasing inflections allowing for averaged values for conversion between heart rate and metabolic rate across EVA (Figure 2A). HR was predicted from the MR/HR conversion metric and showed higher RMSE values across EVAs (Figure 2B). However, intensity of general EVA task workload could be seen when arranging MR values into bins of increasing values. MR/HR metrics showed an increasing trend in addition to increasing trends of HR, when placed in bins of corresponding increasing MR ranges (Figure 2C). Predicted HR using the sorted MR/HR metric values during EVA showed decreased RMSE at higher MR ranges compared to non-sorted MR/HR metrics (Figure 2D).

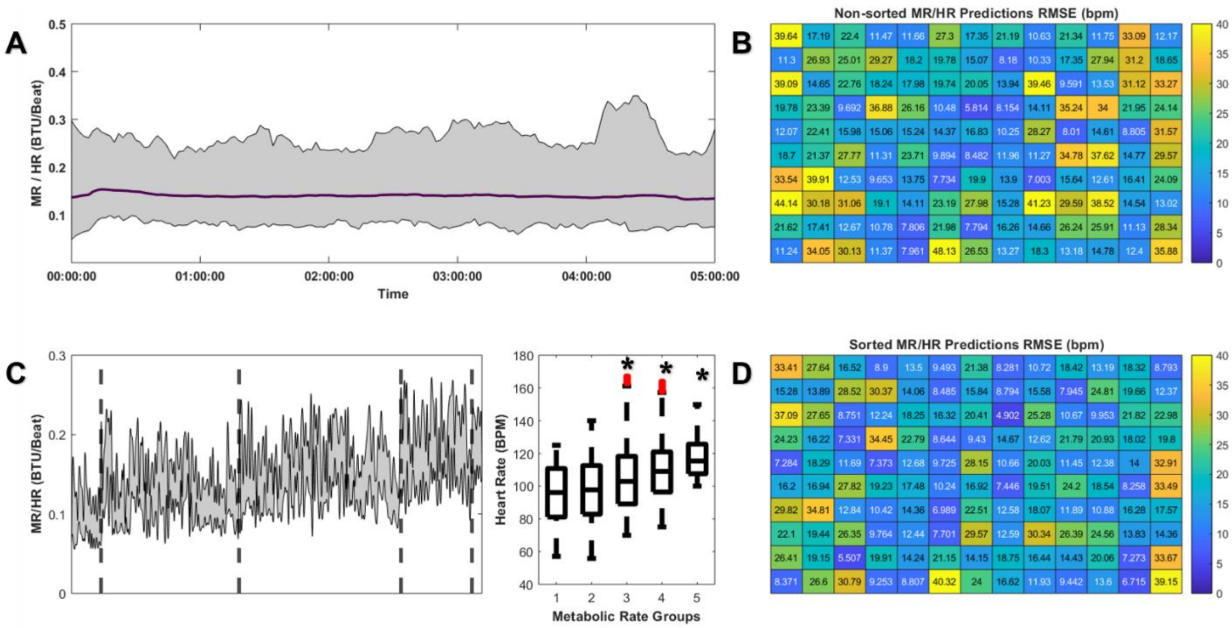

Figure 5. 2: BTU/Beat values were calculated in a new metric of MR/HR to draw correlations between heart rate and metabolic rate during EVA as a conversion scale A. Prediction RMSE of HR from the generated MR/HR scale are presented for individual EVAs B. Metabolic rates were sorted into increasing bins with corresponding sorted MR/HR values and heart rates showing increasing trends (* designates p<0.05 compared to the lowest MR values) C. Predicted RMSE of HR was shown to decrease across EVAs when using the sorted MR/HR scale D.

Further, MR was predicted based on HR values during EVA via a calculated simple linear regression. A regression equation was found drawing relations between HR and MR (F (2923.84) and $P<0.0001$) with an R^2 value of 0.402 (Table 1). As tasks were not common between all EVAs a single simple linear regression was made for each EVA for individual predictions increasing R^2 greater than 0.82. Predicted and original values of metabolic rate showed agreement with individual responses during EVA (Figure 3A, 3D, 3E). Collected regression prediction with individual responses were within predicted confidence levels (Figure 3B). MR/HR conversion metrics showed larger RMSE error as a comparison to regression outputs (Figure 3C). Individual responses however, showed predicted RMSE decreased when using individual crew regressions (89.66 ± 44.24 BTU/hr) compared to MR/HR generated conversion scale (Figure 3E).

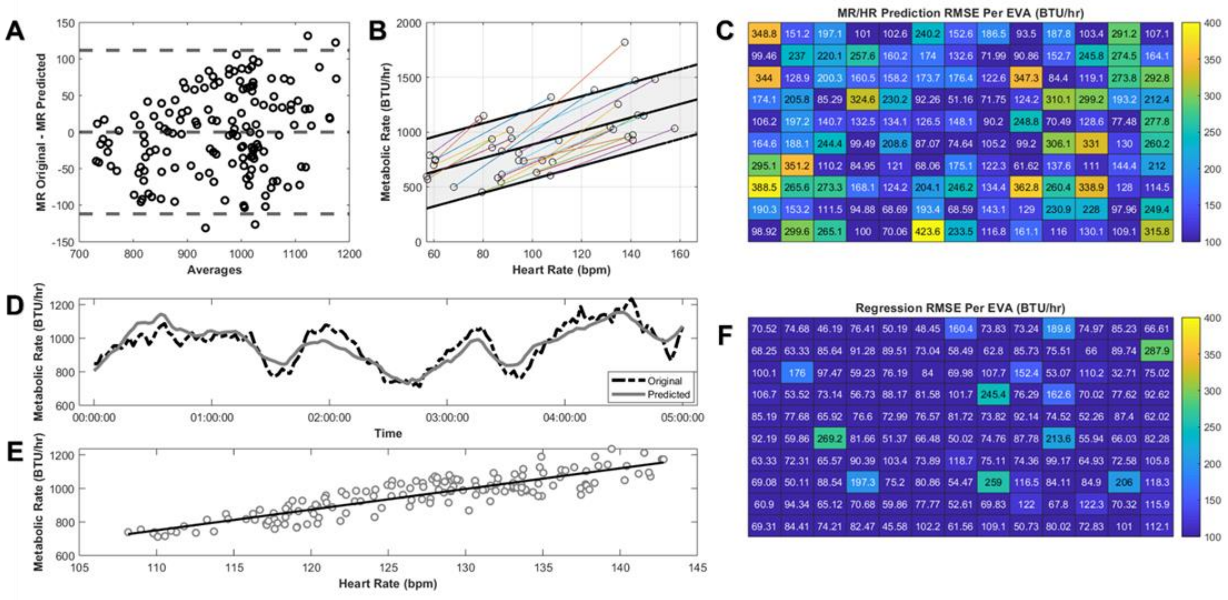

Figure 5.3: Individual crew regression responses show agreement between predicted and original metabolic rate observations A. Individual responses show predictions are within the confidence interval of the larger EVA regression model B. As a comparison metabolic rate predictions were completed using MR/HR which show RMSE values for individual EVAs C. Prediction of single EVA observations of original and predicted metabolic rates using the individual regression model and corresponding linear trend D and E. Individualized regressions for single EVAs show increased quality of predictions with drastically reduced values of RMSE compared to MR/HR predictions F.

5.5 Discussion

In this study, metabolic rate was predicted from corresponding heart rate through a new metric of BTU/beat calculation and simple linear regressions. Using the heart rate method and MR/HR metrics provide a minute-by-minute technique for use in future real-time monitoring. MR/HR metrics provided a BTU/beat observation that was used to predict observations between heart rate and metabolic rate. This metric showed reduced error of prediction of HR utilizing a conversion factor of BTU/beat in correspondence to binned metabolic rate averages from the 132 sets of EVA data. HR and MR did not seem to exhibit drift over the course of EVA. However, decreases in HR and MR slopes from observed from the start of EVA compared to the end of EVA suggests fatigue responses to increased workload, potentially due to dehydration or workload strain [212]. This also could be a factor of task planning to with lighter loads at the end of EVA.

Heart rate was observed to decrease across the duration of EVA for all 132 EVA sets. Similarly, this observation was seen in metabolic rate for the durations of EVA. Comparison between the EVA start workloads to one-hour increments to the end of EVA showed decreasing trends. The prolonged workload of EVA was expected to have an increasing drift of these values. However, normally in 1-G, hydrostatic forces create a gradient distribution of fluid pressure in the body. During a standing state, blood pressure is controlled through afferent stimulus of the mechanically sensitive baroreceptor impulses. The baroreceptor responses in the upper vasculature, localized in the carotid sinus and the aortic arch, lead to the increased HR and systemic vascular resistance (SVR) as a result of vagal withdrawal and sympathetic activation [26]. During weightlessness the phenomenon of headward fluid shifts occurs due to the lack of force pulling the blood towards the legs [155]. The change of microgravity, not normally seen by the cardiovascular system, shifts the responses of the Baroreflex to gain back homeostasis by attempting to control the equalizing pressure. Due to this headward fluid shift the cardiovascular system may be at a predisposition to have increased cardiac output and increased stroke volume. Whereas, heart rate drift is discussed as an increase in heart rate due to constant cardiac output and decreased stroke volume [209]. During microgravity this cardiovascular response of increased cardiac output and increased stroke volume could account for the decrease in HR and corresponding MR during increased workload (Figure 1, Table 1) [148], [213].

It has been thought that these longer stays in microgravity can have a detriment to the autonomic control of blood pressure due to changing vasculature. Hughson et al., were the first to report a decrease in systematic vasculature resistance and increased arterial stiffness of astronauts after six months of flight utilizing pulse width transition time [35]. While, Norsk et al. had shown the effects of weightlessness on the vasorelaxation. Mechanically, the research had shown a 9%

decrease in systemic vascular resistance, while blood pressure and HR were unchanged [36]. Due to the increased fluid shifts in the upper vasculature, Norsk et al. observed, an increase of systemic vasodilation; this dilation is suggested to be they body's attempt to prevent blood pressure increasing. This decrease in systemic vascular resistance and increase in vasodilatory responses also have an effect in increased core body temperature [199]. While some investigations point to headward fluid shifts as a detriment to the cardiovascular system, it could cause more efficient cardiovascular responses to workload through increased cardiac output and stroke volume [18], [148].

Heat production and energy expenditure is directly correlated to HR and HR drift [209]. MR was found to decrease linearly with decreases in HR. This correlated linear response of both HR and MR during EVA allowed for predictions through simple linear regressions (Figure 3D, 3E). Direct comparisons between EVA values could not be conducted as EVAs were completed across different missions, however, a linear regression using 80 % training and 20 % testing of the datset was completed with a reduced RMSE output for prediction. This R^2 was lower due to the workload metabolic rate variation however, still encapsulated individual responses within the regression confidence levels (Figure 3B). The prediction output was improved with R^2 values being reduced when taking individualized crew regressions for partial EVA and predicting subsequent events of EVA metabolic rate. These predictions were corresponding to results seen in Apollo based predictions of HR using RMSE as another metric of evaluation. It was determined that RMSE below 200 BTU/hr was deemed an appropriate amount of error in the prediction [207]. Similarly, MR can be used to predict HR with an RMSE below 10 bpm. In-flight EVA is a noise induced environment the prediction of individual crew responses allowed for an R^2 greater than 0.82 and drastic reductions in RMSE when only taking HR and MR observations (Figure 3F). The developed model technique will allow for redundant and accurate prediction of suited energy expenditure and cardiovascular response to task loads during long EVAs.

5.5.1 Limitations and Considerations

While including a large set of EVA data, the data only focused on observations of metabolic rate and heart rate. Drawing improved correlations could increase the predictive element of the developed models through direct task analysis during EVA. As this dataset was collected from different Shuttle and ISS missions including more metrics could improve the model through a multiple regression increased from a simple linear regression as presented. Similarly, the metric of the MR/HR values determine a BTU/beat by incorporating increased task load evaluation of this BTU/beat metric can be improved. As a corollary, having repeat crew members or subjects could also draw correlations in the development of individualized models for future use on exploration missions.

5.6 Conclusions

Monitoring crew health during spaceflight missions is important to mitigate injury during EVA. Microgravity and spaceflight are unforgiving environments. Prolonged exposure to microgravity produces an array of deconditioned physiologic systems. Among those systems most effected is the cardiovascular system. Tied to the cardiovascular system metabolic energy expenditure changes with altered gravity and workload. In this study correlations between heart rate and metabolic rate during long durations of EVA were drawn to determine if there is an element that can be used to predict fatigue or cardiovascular drift. A new metric was determined as MR/HR measured in BTU/beat that can be used as a conversion scale to predict metabolic rates from heart rates. Further, in this study a simple linear regression model was developed for further predictions of metabolic rate from heart rate determined during EVA. These techniques provide a foundation for further improvement on the model to evaluate crew member state during exploration EVA on future spaceflight missions.

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