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The proposed work has two objectives to improve prediction and assessment capabilities. The first objective is to determine if the generalized equation provided by our new gait mechanics model predicts the metabolic cost of weighted and unweighted walking more accurately than existing generalized equations. Our second objective is to determine how accurately weighted and unweighted walking metabolic rates can be estimated in field settings from simple technologies.

Metabolic rates will be measured from expired gases. The timing of each walking stride, as well as its subcomponents (i.e. the contact and leg swing portions) will be determined from video. In addition, the periods of muscular activity responsible for executing the movements of the walking stride will be also assessed from electrical activity using surface electrodes attached to the skin above target muscles. The forces that subjects apply to the ground during locomotion may be measured from either a force plate or force sensors built into a treadmill. Finally, heart rate monitors to measure heart beat frequency, miniature motion sensors mounted to the shoe or other parts of the body to measure movement speeds and rates may also be utilized.

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## INTRODUCTION

The proposed work has two objectives coordinated to fulfill the overall objective of improving quantitative estimates of locomotor metabolism and activity in field settings. The objective of the first portion of the experimental work is to develop generalized equations that relate height, weight and speed to the metabolic rates incurred during walking. Fulfilling this objective will involve assessing whether the generalized equations provided by our new gait mechanics model will predict the metabolic cost of weighted and unweighted walking more accurately than existing generalized equations under controlled conditions. Our second objective is to determine how accurately weighted and unweighted walking metabolic rates can be estimated in field settings using simple, inexpensive wearable technologies.

Metabolic rates will be measured from expired gases. The timing of each walking stride, as well as its subcomponents (i.e. the contact and leg swing portions) will be determined from video and/or ground reaction force data. In addition, the periods of muscular activity responsible for executing the movements of the walking stride may be assessed from electrical activity using surface electrodes attached to the skin above target muscles. The forces that subjects apply to the ground during locomotion may be measured from either a force plate or force sensors built into a treadmill. Finally, miniature motion sensors and geolocation devices mounted to the shoe or other parts of the body to measure movement speeds and rates will also be utilized. Field trials will be conducted using lightweight, portable indirect calorimeters. Subjects will walk both with and without weighted backpacks during both the laboratory and field trials.

## BODY

In this last scheduled year of the three-year award, our efforts have been primarily focused on data analysis, model development, report and manuscript preparation. Over the course of the last year, we enrolled and tested 13 additional subjects.

In keeping with the focus above, we produced two manuscripts and a technical report that have resulted from efforts in the past year. These documents convey the depth of our modeling and analytic efforts and detail the successes that this award has made possible. These have been provided as attachments to this report.

Some experimental work remains to: 1) complete a 2nd field validation of our walking metabolic model and predictive equation, and 2) fill out our subject pool as needed to develop a robust tool for predicting aerobic fitness from a brief, low-exertion walking test.

**October 2011 through January 2012**

In the three months that elapsed between October 2011 and January 2012 we completed testing on 9 subjects for a total number of 48 subjects. Thirty-four completed our combined walking metabolism and walking aerobic fitness test protocols (requiring three laboratory testing sessions) and 14 completed a shortened version of the protocol. This is up from the 39 total subjects we had tested as of our October report.

To this point, our stature-based metabolic model performed well, accounting for 94% of the variability in walking metabolic rates between individuals and across speeds (with an SEE of 1.07 $mls \bullet kg^{-1} \bullet min^{-1}$).

We continued testing our walking model in overground outdoor trials and 4 additional subjects were tested. Thus far, 16 subjects have completed a three-speed protocol on level asphalt with metabolic measurements being acquired using the Douglas bag technique. The agreement between the treadmill data from the laboratory and the over-ground data for these subjects is good ($R^2$= 0.88; SEE = 0.79 $mls \bullet kg^{-1} \bullet min^{-1}$)

The predictions provided by our stature-based model on the over-ground trials thus far completed is also good ($R^2$= 0.73; SEE = 1.23 $mls \bullet kg^{-1} \bullet min^{-1}$.

In addition, the 48 subjects who were tested for the further development of our stature-based model of walking energy expenditure also completed maximal metabolic rate tests. With this data, we have further developed the two-step algorithm to estimate maximal aerobic power from submaximal heart rates. Since the last quarter, we have continued to refine and enhance the algorithm involved in the two-step process to maximize predictive accuracy. Our algorithms predict maximal aerobic power with an average accuracy between 8.0 and 10.0% for fully independent predictions on the 48 individuals tested ($VO_{2max}$ range = 19 to 67 $mls \bullet kg^{-1} \bullet min^{-1}$). Our average absolute error for these predictions currently stands 4.04 $mls \bullet kg^{-1} \bullet min^{-1}$, and our working SEE is 5.15 $mls \bullet kg^{-1} \bullet min^{-1}$.

Our request to be granted permission to expand the number of subjects tested to meet this objective was approved. Therefore, we increased the number of subjects tested as planned and specifically recruited individuals likely to be at the high and low fit extremes of our healthy population. We will continue to recruit individuals of extreme high and low fitness levels as we refine and finalize the algorithms.

We have continued to work on two manuscripts supported by this award, one on performance and fatigue during brief, high-intensity exercise and a second on our new stature-based model of walking metabolism. The walking paper in progress will further develop the applications of our stature-based model by extending predictive relationships to the complete range of walking speeds per Figure 1 above. The new algorithms predict walking metabolic rates from height, weight and walking speed.

**February 2012 through April 2012**

At this juncture, our stature-based metabolic model continued to perform well, accounting for essentially the same proportion of variance as in the last quarterly report with a similar SEE. At this juncture, the agreement between the treadmill data from the laboratory and the over-ground data remained as stated in the prior report.

In addition, the 49 subjects who were tested for the further development of our stature-based model of walking energy expenditure also completed maximal metabolic rate tests. With these data, we further developed the two-step algorithm to estimate maximal aerobic power from submaximal heart rates. Since the last quarter, we continued to refine and enhance the algorithm involved in the two-step process to maximize predictive accuracy. At this juncture, our algorithms predicted maximal aerobic power with an average accuracy between 8.0 and 10.0% for fully independent predictions on the 49 individuals tested ($VO_{2max}$ range = 19 to 67 $mls•kg^{-1}•min^{-1}$). The average absolute error for these predictions currently stands 4.11 $mls•kg^{-1}•min^{-1}$, and our working SEE is 5.15 $mls•kg^{-1}•min^{-1}$.

Our request to be granted permission to expand the number of subjects tested to meet this objective was approved. Therefore, we increased the number of subjects tested as planned and specifically recruited individuals likely to be at the high and low fit extremes of our healthy population. We have made several strategic efforts to recruit the highly fit aerobic subjects deemed desirable for rounding out our data set and maximizing the robustness of our algorithms. Flyer postings on regional and national running sites have not been successful. More recently, we have had preliminary success with personal contacts provided by a research subject tested previously. We will continue to recruit individuals of extreme high and low fitness levels to the extent we are able to and in the hopes of refining and finalizing our algorithms in the most robust forms possible.

We continued to work on two manuscripts supported by this award, one on performance and fatigue during brief, high-intensity exercise and a second on our new stature-based model of walking metabolism. The first manuscript was submitted in January. A revision of this manuscript, resubmitted with responses and modifications to the critiques provided by the peer-review process, was submitted in March. The manuscript has since been accepted and will appear in the July 2012 version of *Exercise and Sport Science Reviews*. The walking paper in progress will further develop the applications of our stature-based model by extending predictive relationships to the complete range of walking speeds per Figure 1 below. The new algorithms predict walking metabolic rates from height, weight and walking speed.

**April 2012 through July 2012**

In the three months that have elapsed since our last quarterly report, we have focused on data analysis, manuscript preparation and logistical issues for the completing the remaining field trials successfully. Our total number of subjects tested is now 51. Of these, thirty-four have completed our combined walking metabolism and walking aerobic fitness test protocols (requiring three laboratory testing sessions) and 17 have completed a shortened version of the protocol.

Thus far, 21 subjects have completed a three-speed protocol on level asphalt with metabolic measurements being acquired using the Douglas bag technique.

In addition, the 51 subjects who were tested for the further development of our stature-based model of walking energy expenditure also completed maximal metabolic rate tests. With these data, we have further developed the two-step algorithm to estimate maximal aerobic power from submaximal heart rates. Since the last quarter, we have continued to refine and enhance the algorithm involved in the two-step process to maximize predictive accuracy. Our algorithms predict maximal aerobic power with an average accuracy between 8.0 and 10.0% for fully independent predictions on the 51 individuals tested ($VO_{2max}$ range = 19 to 75 mls•$kg^{-1}$•$min^{-1}$). Our average absolute error for these predictions currently stands 4.39 mls•$kg^{-1}$•$min^{-1}$, and our working SEE is 5.62 mls•$kg^{-1}$•$min^{-1}$.

We made several strategic efforts to recruit the highly fit aerobic subjects deemed desirable for rounding out our data set and maximizing the robustness of our algorithms. Flyer postings on regional and national running sites have not been successful. We continued to recruit individuals of extreme high and low fitness levels to the extent we are able to and in the hopes of refining and finalizing our algorithms in the most robust forms possible.

We have continued to work on two manuscripts supported by this award, one on performance and fatigue during brief, high-intensity exercise and a second on our new stature-based model of walking metabolism. The first manuscript was submitted in January. A revision of this manuscript, resubmitted with responses and modifications to the critiques provided by the peer-review process, was submitted in March. The manuscript has since been accepted and will appear in the July 2012 version of *Exercise and Sport Science Reviews*. The walking paper in progress will further develop the applications of our stature-based model by extending predictive relationships to the complete range of walking speeds. The new algorithms predict walking metabolic rates from height, weight and walking speed.

**July 2012 through October 2012**

In the three months that elapsed since our last quarterly report in July of 2012, we continued to focus on data analysis, model refinement, manuscript preparation and logistical issues for the completing the remaining field trials successfully. We also tested 1 additional subject to bring the total number of subjects tested to 52 although the data of the last subject tested has not yet been incorporated into our final analyses and working versions of the algorithms. Of these, thirty-five have completed our combined walking metabolism and walking aerobic fitness test protocols (requiring three laboratory testing sessions) and 17 have completed a shortened version of the protocol.

As presented in our prior quarterly reports, our stature-based metabolic model is performing well, accounting for 94% of the variability in walking metabolic rates between individuals and across speeds per the illustration in Figure 1 (with an SEE of 1.07 $mls \cdot kg^{-1} \cdot min^{-1}$).

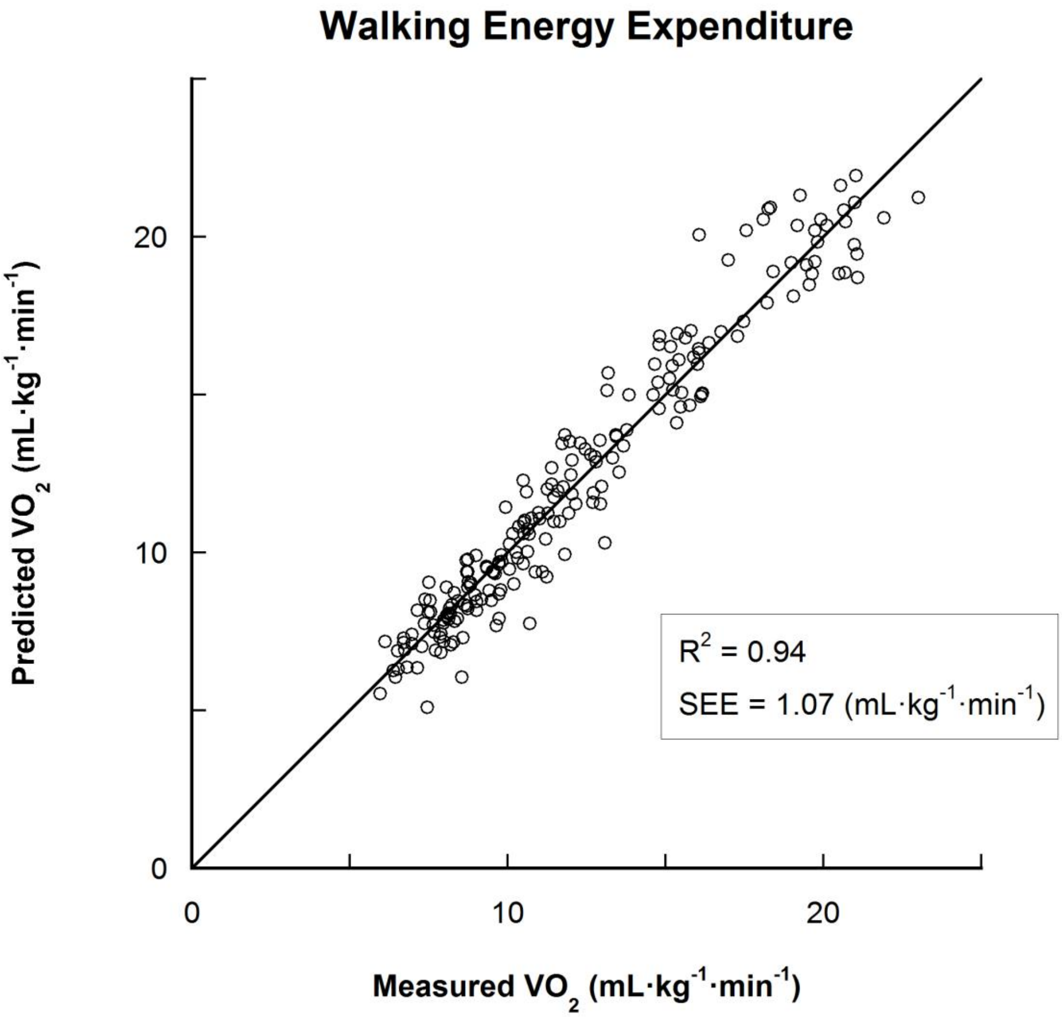


**Figure 1.** The agreement between measured and predicted rates of oxygen uptake (n=34 subjects) at six different treadmill walking speeds from 0.4 to 1.9 meters per second.

At this juncture, 21 subjects have completed a three-speed protocol on level asphalt with metabolic measurements being acquired using the Douglas bag technique. The agreement between the treadmill data from the laboratory and the over-ground data for these subjects is illustrated in Figure 2 below.

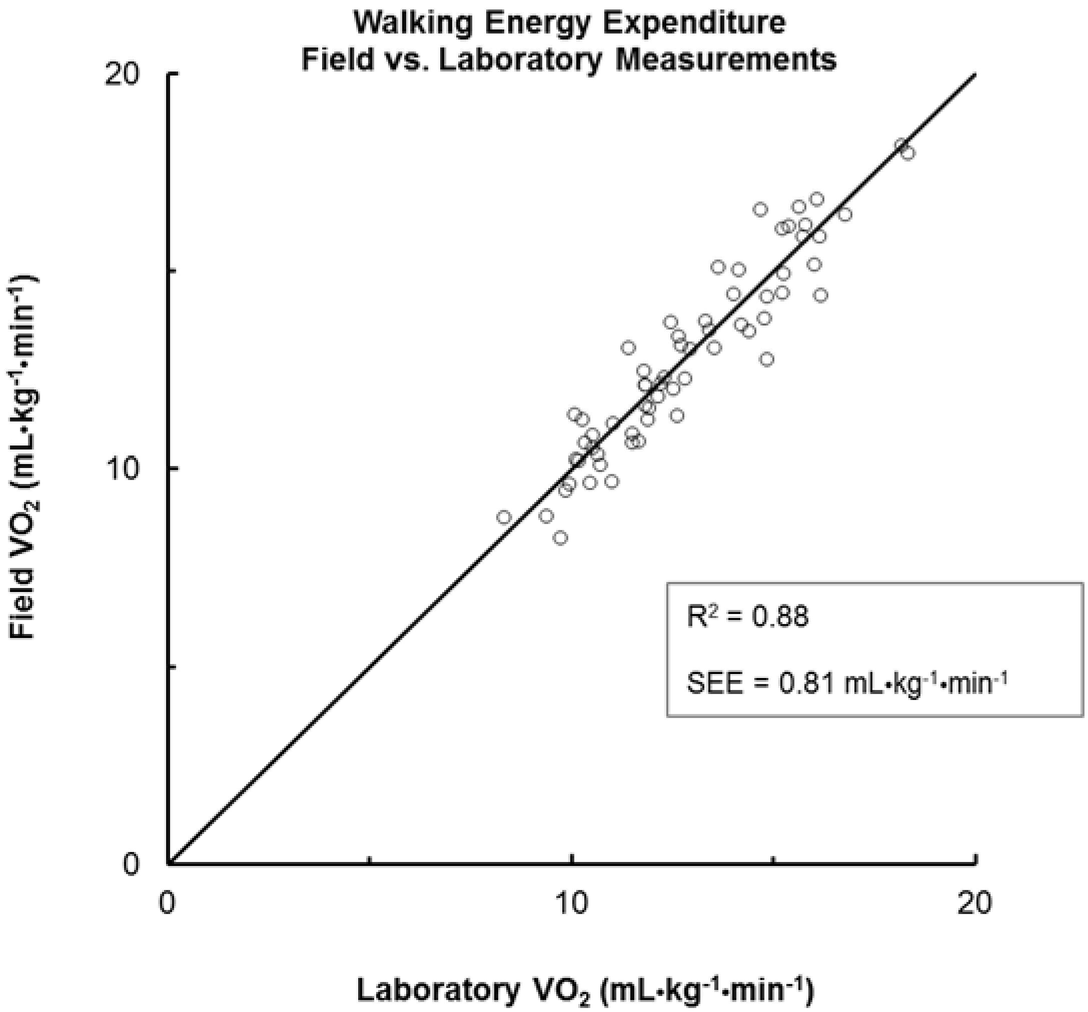


**Figure 2**. The agreement between treadmill and over-ground rates of oxygen uptake (n=21 subjects) at three walking speeds: 1.0, 1.3 and 1.6 meters per second.

The predictions provided by our stature-based model on the over-ground trials thus far completed appear below in Figure 3.

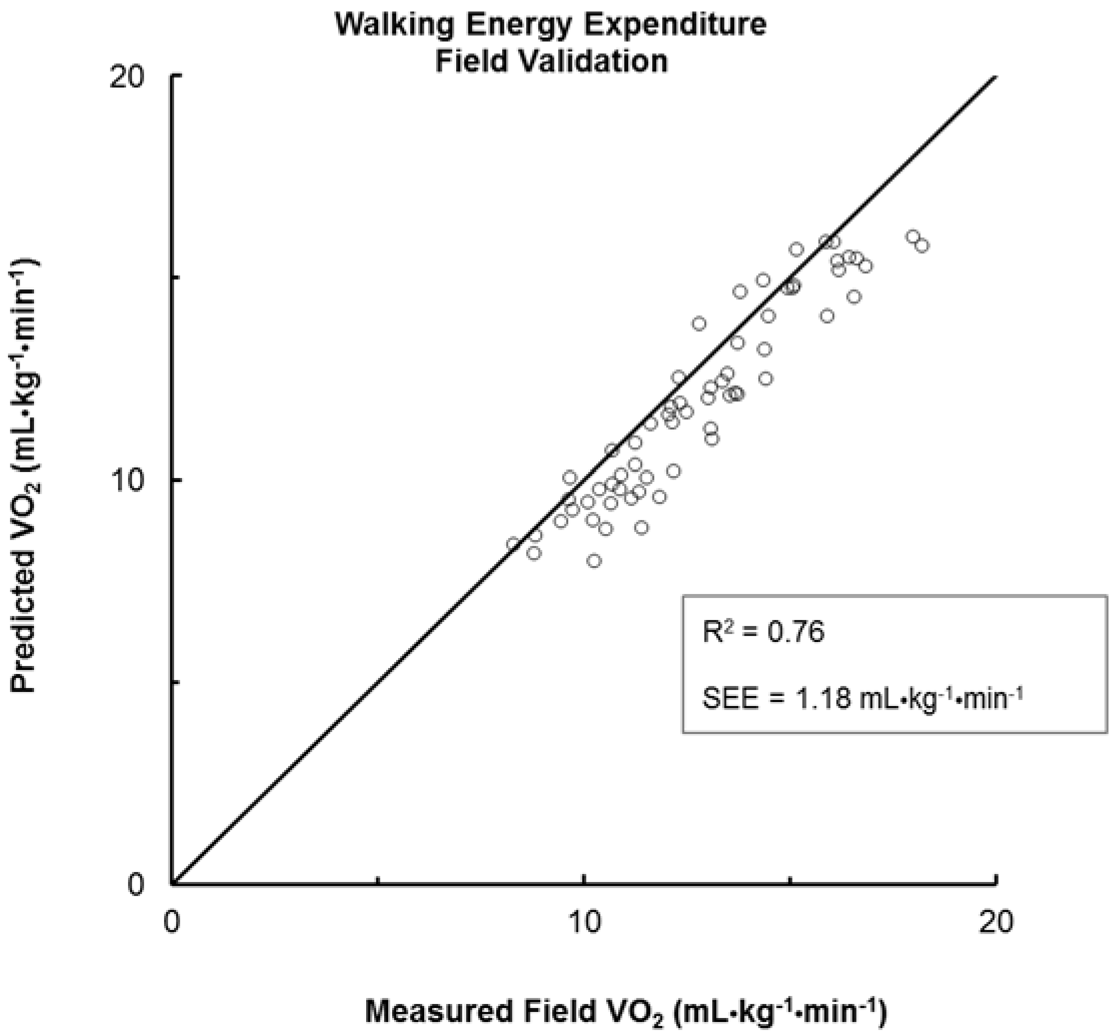


**Figure 3.** The agreement between measured rates of oxygen uptake (n=21 subjects) during over-ground walking at 1.0, 1.3 and 1.6 meters per second vs. the rates predicted by our stature-based model.

In addition, the 52 subjects who were tested for the further development of our stature-based model of walking energy expenditure have also completed maximal metabolic rate tests. Per our previous report regarding these data, we further developed the two-step algorithm to estimate maximal aerobic power from submaximal heart rates. Our current algorithms predict maximal aerobic power with an average accuracy between 8.0 and 10.0% for fully independent predictions on the 51 individuals currently included in the analysis ($VO_{2max}$ range = 19 to 75 mls•$kg^{-1}$•$min^{-1}$). Our average absolute error for these predictions currently stands 4.39 mls•$kg^{-1}$•$min^{-1}$, and our working SEE is 5.62 mls•$kg^{-1}$•$min^{-1}$.

We have made several strategic efforts to recruit the highly fit aerobic subjects deemed desirable for rounding out our data set and maximizing the robustness of our algorithms. These efforts include a request to pay the travel expenses to bring very highly fit individuals to Dallas from other regions of the United States. We are awaiting a decision on this request of late August. We will continue to recruit individuals of extreme high and low fitness levels to the extent we are able to and in the hopes of refining and finalizing our algorithms in the most robust forms possible.

We have continued to work on manuscripts supported by this award. Per our last report, a manuscript on performance and fatigue during brief, high-intensity exercise published in July, 2012 of *Exercise and Sport Science Reviews*. A manuscript that introduces a new "height-weight-speed" model of walking metabolic rates has been drafted in full and will be submitted as soon as the final details of the statistical procedures and analysis are determined and incorporated. To better understand the contributors to walking metabolism, we have most recently begun exploring modeling best solutions possible with one, two and three component models taking a limited variety of forms.

Our work on the mechanics of sprint running performance received considerable attention during the summer months leading into the Olympic and Paralympic Games. Major stories appeared in: the BBC Future Magazine, The Economist, Discovery News, Reuters, Scientific American, Sports Illustrated, Sports Illustrated Kids and Wired Magazine among other publications. This research was also covered by Science Magazine's online chat on "Science at the Olympics" as well as the BBC 4 radio and Public Radio International.

## KEY RESEARCH ACCOMPLISHMENTS

### KEY RESEARCH ACCOMPLISHMENTS IN The 1ST QUARTER:

Subject recruitment and testing was expanded to 48 subjects, 34 have completed our three-session walking model/walking testing, and all 48 have completed testing for maximal aerobic power.

Field testing of our stature-based walking model was expanded from the 12 subjects tested in the last report to a total of 16 that have now completed the outdoor over-ground measurement protocol.

We requested and obtained both required permissions from the SMU IRB and HRPO to add a 2nd outdoor validation on a grass field.

Our walking index of aerobic fitness algorithms was refined in several ways that more successfully use simple and readily available inputs such as height, weight, walking speed and heart rate to predict maximal aerobic power. The specific procedure and algorithms utilized for our walking aerobic fitness index have now progressed to the invention disclosure stage. An invention disclosure has been submitted to the SMU Office of Research and Graduate Studies and is under consideration at this time.

We finished a draft of an invited manuscript for Exercise and Sport Science Reviews entitled "Sprint Exercise Performance: Does Metabolic Power Matter?" that was nearly submission ready. Much of the experimental work and intellectual discovery in the manuscript would not have been possible without the support provided by our TATRC award.

## KEY RESEARCH ACCOMPLISHMENTS IN THE 2ND QUARTER:

We made continued progress with algorithm and model refinement as a result of continued data analysis pursuant to both primary objectives: 1) advancing our stature-based model of walking metabolic rates, and 2) using our walking model to develop a brief, simple and accurate walking test of aerobic fitness.

We have had an invited manuscript proceed successfully through peer-review process and that is now in press. The manuscript is in a top journal and has broad implications for the scientific and applied basis of performance, fitness and exercise testing for brief, high-intensity exercise. The manuscript is entitled "Sprint Exercise Performance: Does Metabolic Power Matter?" Much of the experimental work and intellectual discovery in the manuscript would not have been possible without the support provided by our TATRC award.

We continued logistical preparations to undertake field walking tests of our maturing stature model which will involve global positioning system speed and position data to move our algorithms toward widely available field usage. We also continued recruiting efforts to identify highly fit aerobic volunteers, albeit with limited success through the last quarterly period.

Subject recruitment and testing has been expanded to 49 subjects, 34 have completed our three-session walking model/walking testing, and all 49 have completed testing for maximal aerobic power.

KEY RESEARCH ACCOMPLISHMENTS IN THE 3RD QUARTER

We continued to analyze and develop algorithms for both primary grant objectives: 1) advancing our stature-based model of walking metabolic rates, and 2) using our walking model to develop a brief, simple and accurate walking test of aerobic fitness.

We had an invited manuscript proceed successfully through peer-review process and that is now in press. The manuscript is in a top journal and has broad implications for the scientific and applied basis of performance, fitness and exercise testing for brief, high-intensity exercise. The manuscript is entitled "Sprint Exercise Performance: Does Metabolic Power Matter?" Much of the experimental work and intellectual discovery in the manuscript would not have been possible without the support provided by our TATRC award.

We continued logistical preparations to undertake field walking tests of our maturing stature model which will involve global positioning system speed and position data to move our algorithms toward widely available field usage. We also continued recruiting efforts to identify highly fit aerobic volunteers, albeit with limited success through the last quarterly period.

Subject recruitment and testing has been expanded to 51 subjects, 34 have completed our three-session walking model/walking testing, and all 51 have completed testing for maximal aerobic power.

KEY RESEARCH ACCOMPLISHMENTS IN THE 4TH QUARTER:

We made additional progress with algorithm and model refinement on both primary grant objectives: 1) advancing our stature-based model of walking metabolic rates, and 2) using our walking model to develop a brief, simple and accurate walking test of aerobic fitness.

We have submitted a travel authorization request for the resources needed to bring highly fit subjects to the laboratory for testing. We also submitted a request for a no-cost extension in late August. We are awaiting decisions on these requests in order to be able to continue with the remaining work into the next quarter and beyond so the work can be completed successfully and fully translated into deliverables for TATRC, the DOD and general public.

We have begun field data acquisition in the field to test our new generalized equation outside of the laboratory. Field testing will include global positioning system speed and position data to move our algorithms toward widely available field usage.

We completed the modeling and data analysis to introduce a new generalized equation to predict walking metabolic rates. The scientific background, methods and analysis leading to the new generalized equation proposed is presented in the manuscript attached. This now completed draft is the first submission to the *Journal of Applied Physiology*.

YEAR-END SUMMARY OF KEY ACCOMPLISHMENTS

The major accomplishments for the last year of activity are as follows:

1) The integration of the mechanics and energetics of sprint exercise performance.

- See attached manuscript

2) The formulation of a new model and generalized equation for predicting metabolic rates during walking on firm level surfaces.

The new equation establishes the importance of a major factor that has not been included in prior models and predictive equations: stature. We have formulated and introduced a new generalized equation to predict walking metabolic rates that is appreciably more accurate than existing standards (Pandolf et al for military usage and the American College of Sports Medicine equation for general population usage).

- See attached manuscript

3) The development of a new technique for predicting maximal aerobic power from a brief, practical walking test.

- See attached technical report

## REPORTABLE OUTCOMES

Please see key research accomplishments and attached reports.

## CONCLUSIONS

We have compiled a large portion of the data bases essential to further development and refinement of our stature-based model of the energy cost of walking and the development of a walking test of aerobic fitness. In both cases our data and modeling efforts incorporating these data have translated into successful algorithms that should prove useful, practical and valuable for military, clinical and general field usage. In the coming year we look forward to finalizing our data sets, pursuing intellectual property and publishing our results.

REFERENCES:

American College of Sports Medicine Guidelines for Graded Exercise testing and Prescription, 7th edition. Philadelphia, PA: Lippincott, Williams and Wilkins, 2006.

Pandolf KB, Givoni B, Goldman RF. Predicting energy expenditure with loads while standing or walking very slowly. *J Appl Physiol* 43: 577-581, 1977.

APPENDICES:

None