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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Here, load carriage interventions for walking *energy expenditure* and *running speed* have been designed to: 1) advance existing models and 2) contribute needed data to the broader effort to develop load-carriage decision-aid tools for modern soldiers. We hypothesize first that our height, weight (including load), speed, and grade algorithms proposed will allow walking metabolic rates to be predicted to within 6.0 and 12.0% in laboratory and field settings, respectively. We hypothesize second that the speed-load carriage algorithms will allow load-induced decrements in all-out sprint running speeds to be predicted to within 6.0% in both laboratory and field settings. Respective load-carriage algorithms for *walking energy expenditure* and *running speed* will be developed and tested (Technical Objectives 1.0 and 2.0) in the laboratory and the field.

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INTRODUCTION

The Need for Load Carriage Decision-Aid Tools

Load carriage is a foot-soldier requirement with direct consequences for a broad array of physiological, performance and health outcomes. Metabolic energy expenditure, heat production, macronutrient requirements, water requirements, and injury risks are all directly elevated by the weight of the equipment soldiers carry while both short- and long-term mobility are substantially reduced (Knapik et al., 1996; Knapik et al., 2004). Clearly, the physiological stresses and mobility losses induced by load carriage do not constitute desirable field outcomes. Indeed, anecdotal (Knapik & Reynolds, 2010) and formal (Dean, 2004) accounts of the negative consequences of pack overloads are readily available from a multitude of field combat situations. In both modern and historical warfare environments alike, the physiological status and mobility of foot soldiers influence combat performance, wound and survival rates. Accordingly, exacting considerations of the value of carried equipment evaluated against the negative performance, wound and mortality consequences of added weight are a matter of vital military importance.

A priori, one might expect that the major advances in both material science and electronics in the modern era would provide soldiers with more effective equipment while simultaneously reducing the loads soldiers carry. However, the historical record indicates a marked trend in the opposite direction. During the 150-year period from the Civil War through the present day, the pack weights of American foot soldiers have *increased* by a factor of approximately 3-fold, from 15 kg during the Civil War to 35 kg in World War II to approximately to 45 kg in Desert Shield (Knapik & Reynolds, 2010), and 45 kg or above in Afghanistan (Dean, 2004). For an average-sized male US soldier, a load of 45 kg constitutes well over 50% of the body's weight. Thus, the theoretical potential for technological advances in equipment and materials to lighten the pack and total body loads carried by modern foot soldiers has not been realized.

This brief consideration of the historical trends for the loads carried by US soldiers across different eras begs two immediate questions: are the loads carried by modern soldiers excessive? And if so, how harmful is the additional weight carried to warfighter performance?

This answer depends on a fundamental and long-standing load carriage trade-off assessment that balances the *benefits of the equipment carried* vs. the *detrimental performance consequences* imposed by carrying additional weight. On a qualitative level, the benefits of modern body armor, firepower, and communication equipment are relatively obvious, as are the negative physiological and mobility consequences of carrying heavy loads. However, at present, the data needed for quantitative, evidence-based considerations are unavailable. Consequently, well-informed decisions about the pack and total body loads that will be most effective for soldiers in operational environments are not possible.

Given that warfighter field effectiveness is crucial to the efforts of the US military, moving beyond qualitative considerations of the load carriage cost-benefit trade-offs constitutes minimum due diligence to the soldiers in the field as well as to the enormous national investment in our military initiatives. The work proposed here will contribute to a broader experimental work effort to develop **load-carriage, decision aid tools** that take an evidence-based approach to determining loads for foot-soldiers. The specific experimental work we propose focuses on the cost, or detriment side of the load carriage trade-off equation. This work is expected to provide data that are currently lacking, but necessary for informing strategic decisions regarding pack and total load carriage weights.

We present a series of experiments designed to quantify the negative physiological and performance consequences of the loads modern soldiers carry. The work has been formulated using two promising physiological-mechanical models: 1) a stature-based model to explain walking energy expenditure, and 2) a ground force model to explain brief, all-out running speeds. Fulfilling our experimental objectives should allow predictions of the specific physiological, performance and mobility decrements that would be expected across a broad continuum of potential loads.

Objective One: Walking Energy Expenditure

Previous Scientific Efforts of Direct Military Relevance: Because metabolic rates are so fundamentally related to physiological status and sustained performance capabilities, the Army has a long-standing interest in developing techniques to predict and monitor the metabolic rates of soldiers walking in the field. As with most efforts to acquire or predict physiological data in field environments, this has proven to be a challenging undertaking. However, modern monitoring capabilities and improved predictive modeling should allow for meaningful progress.

The pioneering efforts of Pandolf and others in the 1970's (Givoni & Goldman, 1971; Pandolf et al., 1977) established generalized equations that predict the metabolic rates of walking soldiers from total weight (i.e. body weight + load), speed and grade. However, the utility of these equations depends heavily on the ability to acquire walking speed and grade data in the field. This ability was formerly quite limited, but in recent decades has become fully feasible and highly accurate.

In part, because the ability to monitor speed and distance in field environments limited the original applicability of the Pandolf et al. equations, other approaches were pursued. In the 1990's, Hoyt and colleagues (Hoyt et al., 1994; Hoyt & Weyand, 1996; Hoyt et al., 2004; Weyand et al., 2001) adopted an innovative technological approach that, in contrast to the Pandolf approach, did not require speed and distance data. Hoyt devised a bio-monitoring strategy to predict locomotor metabolic rates from the body's weight and the periods of foot-ground contact. This approach was inspired by algorithms (Kram & Taylor, 1990) that explained the metabolic rates of different-sized terrestrial running and hopping animals. Hoyt and colleagues successfully developed biosensors that accurately monitored ambulatory foot-ground contact times and predicted metabolic rates under some conditions (Hoyt et al., 1994; Hoyt et al., 2004; Weyand et al., 2001). However, this approach was not without limitations. Foot-ground contact monitoring requires a functioning sensor and a wireless network, and current monitors cannot detect the surface inclinations that have a substantial effect on walking energy expenditure (Margaria et al., 1968; Minetti et al., 1994; Minetti et al., 2002).

Modeling Walking Metabolism: Recently, we have developed a promising model for predicting walking metabolic rates that combines the strengths of the Pandolf and Hoyt approaches that can be readily implemented in the field using the accurate geo-location systems now available.

Our model may advance predictive accuracy beyond that provided by the two generalized models most commonly used to estimate the metabolic rates of human walkers at present: the Pandolf and American College of Sports Medicine (ACSM) equations. Both use *body weight* and *walking speed*, but not *stature* to predict metabolic rates. Although comparative physiologists have long recognized (Alexander, 1976; Taylor et al., 1982; Kram & Taylor, 1990) that the mass-specific metabolic cost of locomotion varies in a systematic manner with the linear dimensions of the body, the leading models for predicting locomotor costs of humans have not incorporated body or leg lengths. The inverse relationship between the body's length (i.e., height) and the mass-specific metabolic rates of individual human walkers has been recently demonstrated (Weyand et al., 2010)

The Stature-Based Model of Walking Metabolism: Our new stature-based model of walking energy expenditure (Weyand et al., 2010) includes three fully independent variables: body mass, stature and walking speed. The quantitative form of the model is as follows:

$$E_{metab} = RMR + C_1 \bullet RMR + C_2 \bullet V^e/Ht \qquad \text{(eq. 1)}$$

where E_{metab} is the body's total metabolic rate, RMR is resting metabolic rate, V is the velocity of walking, and Ht is height. C_1 and C_2 are empirically derived coefficients, and e is an exponent that quantifies equivalent walking velocities for individuals who differ in height. All metabolic rates in the equation are expressed in mass-specific terms.

In our model, RMR is the body's minimum or baseline rate of energy expenditure, the quantity ($C_1 \bullet$ RMR) represents the factorial increase above resting metabolic rate needed to maintain a walking posture (i.e. a postural metabolic rate, or PMR), and the term ($C_2 \bullet V^e/Ht$) describes the curvilinear, or exponential, increase in mass-specific metabolic rates that occurs with increases in walking velocities standardized to height in accordance with the original suggestion of Alexander (Alexander, 1976; Alexander, 2003) to use the Froude Number (= V^2/gravity • leg length). The product of our slightly modified (for utility and convenience) model term V^e/Ht, and the coefficient C_2, represents the metabolic energy expended to lift, support and accelerate the body's center of mass with each step as walking speed is increased.

Two critical assumptions were involved in our development of the stature-based model to predict walking metabolic rates. First, we assumed that the mass-specific **metabolic energy expended per stride is the same at equivalent walking speeds** regardless of the height and weight of the individual. Second, we assumed that individuals who differ in stature **walk in a mechanically similar way at equivalent walking speeds** (i.e. the same Froude Number or value of V^2/Ht). Here, mechanical similarity is defined as stride lengths and times being related by a constant proportion across individuals of different heights.

Extending the Stature-Based Model to Load Carriage and Graded Walking:

Load Carriage: Two aspects of the model seem promising with respect to extending the stature-based model to the load carriage conditions: the predictive accuracy of the model on the independent and heterogeneous subjects evaluated so far, and a clear conceptual and quantitative basis from which to predict the effect that loading will have. Per below, our stature-based model breaks total walking metabolism into resting and walking components.

$$\dot{E}_{metab} = \underbrace{RMR}_{\text{Resting}} + \underbrace{C_1 \cdot RMR + C_2 \cdot V^e / Ht}_{\text{Walking}}$$

Because the relationship between the weight supported and both of the walking, or non-resting component of our model is 1:1, the predictions of the model for the effect of loading are straightforward: loading will increase the *walking* portion of the total metabolic rate in direct proportion to the load added. Thus, a load equal to 10% body's weight will increase walking metabolic rates by 10%; a load equal to 20% of body's weight will increase walking metabolic rates 20%, etc.

While there is a relatively large body of literature on the consequences of loading for walking metabolism (Bastien et al., 2003; Das & Saha, 1966; Duggan & Haisman, 1992; Falola et al., 2000; Griffin et al., 2003; Holewijn, 1990; Martin & Nelson, 1986; Pimental & Pandolf, 1979), none of the studies available provide the data needed to evaluate the predictive accuracy of the stature-based model under these conditions. Two quantitative issues prevent this: existing data sets and models have not included the influence of stature on walking metabolism, and previous studies have not quantified or reported resting metabolic rates that can be quantitatively related to the resting and postural terms in our model. However, the best data available for evaluating our model (Griffin et al., 2003) indicate that loading results in gross walking metabolic rates being elevated slightly less than in direct proportion to load, while net walking rates (subtracting a standing value) are elevated in slightly greater than 1:1 proportion are consistent with our model predictions.

Graded Walking: Similarly, our expectation is that our model will also apply to graded walking, although per above, quantitative evaluations of our model using the existing literature (Margaria, 1968; Minetti et al., 1994; Minetti et al., 2002; Wanta et al., 1993) are not possible. For graded walking, our approach will be to extend our findings of a constant metabolic cost per stride at equivalent speeds for different individuals to inclined and declined conditions. Under level walking conditions, we found that the lower mass-specific metabolic rates of taller vs. shorter individuals are fully explained by differences in body lengths (i.e. height) and proportional differences in the horizontal distance traveled with each stride (i.e. stride length). Extending our stature-based model to explain metabolic rates during inclined and declined walking involves similar quantification of the distance traveled by the body during each stride. During horizontal walking, including only the horizontal displacements is sufficient. During graded walking, our stature-based model predicts metabolic rates will be a function of both the *horizontal* and *vertical* displacements of the body over the course of each stride. Stride lengths during graded walking are expected to be proportional to stature at equivalent walking speeds as during horizontal walking. However, the vertical displacements of the body over the course of each stride will be a function of both the surface grade and stature. Per intuition, the vertical distance per stride traveled will be greater on any inclined or declined walking surface for taller vs. shorter individuals. Accordingly, metabolic rate deviations from the level condition for taller vs. shorter individuals are also expected to be greater on any given incline or decline. Mechanically, this is most easily conceptualized as the metabolic cost per stride increasing and decreasing in accordance with the positive and negative displacements of the body during each stride. This metabolic pattern is well described in the comparative literature for large and small animals (Taylor et al., 1972), but the data needed to assess humans of different statures is unavailable.

Our expectation is that we can use stature and percent grade to quantify this effect. In the specific terms of our model, our expectation is that our coefficient, C_2 that describes the increases in metabolic rate in relation to increases in equivalent walking speeds, will have the same value for any given positive or negative vertical displacements of the body per stride. Although this relationship will need to be determined empirically, we can make the simple prediction that the value of C_2 during inclined and declined walking will be proportional to the product of the stature of the individual and the percent grade of the surface (i.e. $C_2 \propto Ht \bullet \%$ grade).

The experiments proposed here represent the most fundamental empirical steps needed to extend and validate our stature-based model. Once the basic work needed to develop algorithms including load, incline and decline conditions has been completed, additional work to incorporate the effects of fatigue (Epstein et al., 1988; Patton et al., 1991), terrain (Pandolf et al., 1977) and very steep downhill grades (Margaria, 1968; Santee et al., 2001) may then be explored in the context of the model.

Objective Two: Sprint Running Speed

Previous Scientific Efforts: The scientific literature on the basis of brief, all-out running performance is far less extensive than that devoted to the energy cost of walking. Early efforts focused primarily on explaining performance in terms of the metabolic power available for these events (Hill, 1925; Hill, 1950; Ward-Smith, 1985; Ward-Smith, 1999; Ward-Smith, 2000). While some investigators have continued to use metabolic models to explain these performances (Rittweger et al., 2009), the predominant scientific focus has shifted to mechanical models (Bundle et al., 2006; Usherwood & Wilson, 2005; Usherwood & Wilson, 2006, Chang & Kram, 2007; Weyand et al. 2000; Weyand et al., 20006; Weyand et al., 2010) to explain sprint exercise performances. In our view, this shift is scientifically warranted as mechanical approaches can directly explain the motion of the body and promising force models using this approach are being developed (Weyand et al., 2006; Weyand et al., 2010). In contrast, metabolic models continue to be difficult to validate at present due to the ongoing inability to quantify the whole-body anaerobic and total metabolic energy released during sprinting (Bangsbo, 1998; Van Pragh, 2007).

For the purposes of predicting sprint exercise performance here, we have opted to quantify load-induced decrements in speed as fractional decrements from the unloaded condition. Our interpretation of the existing literature indicates that this approach is likely to provide the greatest predictive accuracy from a simple, practical model. There are at least two sound, literature-based reasons for adopting this approach. First, maximal sprint performances vary considerably between individuals for physiological and mechanical reasons that are incompletely understood and likely cannot be modeled simply. Second, the relationship between all-out sprint running speeds and the average ground forces applied during each step, both within and across individuals, is reasonably linear during sprint running (Weyand et al., 2000; Weyand et al., 2010) which simplifies model predictions.

We expect to be able to predict load-induced decrements in speed with a high degree of accuracy because loads are not likely to alter the maximum forces runners can apply to the ground, but will predictably increase the ground force required to run at any speed. Accordingly, we should be able to use a runner's force maximum at his or her unloaded sprinting speed maximum, load-induced increases in the ground forces required, and the general force-speed relationship to predict load-induced decrements in all-out speed.

Our speed model takes the simple following form:

$$V_L = C_1 \bullet (L/W_b) \bullet V_{UL} \qquad \text{(eq. 2)}$$

where V_L is the maximum velocity of loaded running for all-out runs of brief duration, W_b is body weight, L is the weight of the load carried, C_1 is the coefficient describing the load-induced decrements in speed resulting from fractional additions to the body's weight (L/W_b) via loading, and V_{UL} is the maximum velocity of running in the unloaded condition.

Our force-speed model has its basis in both basic Newtonian mechanics and the ground force capabilities of individual runners. An extensive body of scientific evidence supports the view that a primary mechanical requirement of running is supporting the body's weight against gravity. Successful characterizations of running energetics and even speed and distance monitoring have been realized from this conceptual starting point (Kram & Taylor, 1990; Weyand et al., 2001). Our force-speed model also begins with this basic recognition.

The mechanical basis of our empirically-formulated force model of sprint running is most easily understood by considering how the ground contact and aerial phases of a running stride change across speed for individual runners. The relative durations of the aerial and foot-ground contact phases of a running stride vary with speed. As runners increase their speeds, they spend relatively more time in the air and relatively less time on the ground. Consequently, the ground support forces that runners apply increase in an approximately linear fashion with speed and are set by body mass. For runners regardless of ability, stance-averaged ground support forces are 1.5 times the body's weight while jogging, and increase to 2.0 times the body's weight or more when running at sprinting speeds.

Here, we expect that loading will result in proportional increases in the stance-average ground reaction forces required with little effect on the time course of ground force application. This result has also been reported from studies examining loaded running at slower speeds (Chang & Kram, 2000). The consistency observed in the foot-ground contact times at any given speed across different loads suggests that our general approach is sound

Beyond this, we have found that the limit to running speed occurs when runners reach that speed at which they are repositioning their limbs as quickly as possible while simultaneously applying maximum ground forces. Contrary to intuition, the minimum times runners require to reposition their limbs at their top running speeds does not vary in relation to how fast they can run. Consequently, individual differences in speed are explained all but entirely by the mechanics of the stance phase. These mechanical observations support a modeling approach that focuses on the ground force required and available for speed.

At present, firm predictions of the decrements in brief, all-out running speeds that will occur with loading and that will be quantified by the coefficient C_1 in our force-running speed model are difficult. This is the case because only small number of studies to date have examined the effects of loading on sprint running performance (Alcaraz et al., 2008; Cronin et al., 2008; Holewijn & Lotens, 1992). The few studies that do present loaded and unloaded all-out sprinting speed data do so under conditions that make more generalized predictions difficult, and none of these studies include the ground reaction force data. The most informative study with respect to our experimental objectives here is that of Holewijn & Lotens (1992) who reported that a load equal to 21% of body weight reduced all-out running velocities by 13 and 18% for all-out 80- and 400-meter runs. More recently, Alcaraz et al. (2008) reported only 3% reductions in brief, all-out running speeds with loads equal to 9% of the body's mass, while Cronin et al. reported fractional reductions in all-out loaded sprinting speeds that were approximately half as large as the fractional increases in load/body weight ratios. The disparity in the different results reported to date could result from a large number of factors, and is therefore difficult to interpret. These empirical results project a C_1 value in our model somewhere between 0.4 and 1.0.

Fractional reductions in brief, all-out running speeds that are, in some cases only half as large as the fractional loading of the body's weight reported are surprising. The relatively shallow slope of the force-speed relationship portends a much greater sensitivity. The mechanistic factors that explain a much more limited effect than would be theoretically expected from unloaded force-speed data only are almost certainly rooted in the mechanics of the stance phase ground force application that occurs under loaded conditions. These likely involve mechanical adaptations to loading that improve the leverage of the limb (Biewener et al., 2004) and thereby reduce the muscle forces required in relation to the load being carried.

However, in the complete absence of ground reaction force data or the accompanying video data to determine limb leverage, speculating about the adjustments that may constrain load-induced decrements in speed is difficult. The limited existing data available point to a critical need to acquire ground reaction force and video data under a variety of load and duration conditions to develop a robust predictive model. These data should provide the key to understanding how musculoskeletal mechanics, loading strategies, training and conditioning strategies, and conceivably external aids like exoskeletons, may be utilized to minimize detrimental losses in the short-term mobility of soldiers that result from carrying heavy loads.

BODY

The majority of the first calendar year of the award was devoted to the submissions to multiple review authorities to acquire approval for testing human subjects. Final approval was granted in late December of 2012. The first four months of the 2013 calendar year have been devoted to experimental set-up, experimental design, protocol development and refinement, and subject recruitment. As the first year of the award closed, experimental preparations and protocol refinement were largely concluded and we were poised to begin data collection in accordance with the objectives and approach below:

The load carriage experiments have two specific objectives: 1) to develop and validate algorithms that predict walking metabolic rates from height, weight (including load), speed and grade, and 2) to develop and validate algorithms that predict brief, all-out running speeds from the body and pack weights of the individual. These objectives will be pursued in parallel per the following experimental timeline.

Objective 1 – Walking Energy Expenditure:

We intend to acquire energy expenditure data in the laboratory on those subjects on whom our predictive metabolic equations will be developed using our stature-based model. Subjects will complete walking trials at a number of different walking speeds treadmill grades while their rates of oxygen uptake and energy expenditure are measured.

We will also complete the aforementioned laboratory walking trials across speed and grade needed for our original subjects as needed for algorithm development. In addition, we will undertake field data acquisition by having subjects will undergo a field march on a surveyed field course of known elevations and grades while instrumented to acquire the metabolic and position data.

Objective 2 – Sprint Running Speed:

We will first conduct high-speed running tests in the laboratory on subjects under three different loading conditions: unloaded, +15% body weight, and +30% body weight. Subjects will complete protocols to determine their maximum speeds for efforts ranging from 2 to 90 s while force and video data are acquired.

Next, we will acquire all-out overground running data in both indoor and outdoor settings on subjects. These subjects will complete 25 meter runs indoors and 60 meter runs outdoors under four different loading conditions: unloaded, +15% body weight, +30% body weight, and +45% body weight. Simultaneous force and video data will be acquired during the indoor 25-meter running trials.

KEY RESEARCH ACCOMPLISHMENTS

Key accomplishments over the 12 month reporting-period of the grant year were as follows:

In the first quarter of the last reporting year (April through June of 2013), we

1) Finalized the testing set-ups and protocols for both the loaded walking and running objectives. This included augmenting the treadmill frame with scaffolding to accommodate the downhill conditions.
2) The protocol for unloaded walking across speed and incline for algorithm development was tested and refined.
3) Weighting material, packaging, load distribution and related logistics were developed.
4) Back-pack modifications were made for subject comfort. These included switching backpack type for subject comfort and safety. The newer version identified provided greater shoulder padding and comfort.
5) Standardized footwear was purchased to accommodate research subjects.

The pilot data available for guiding our walking protocol development at this juncture appears in Figure 1 below.

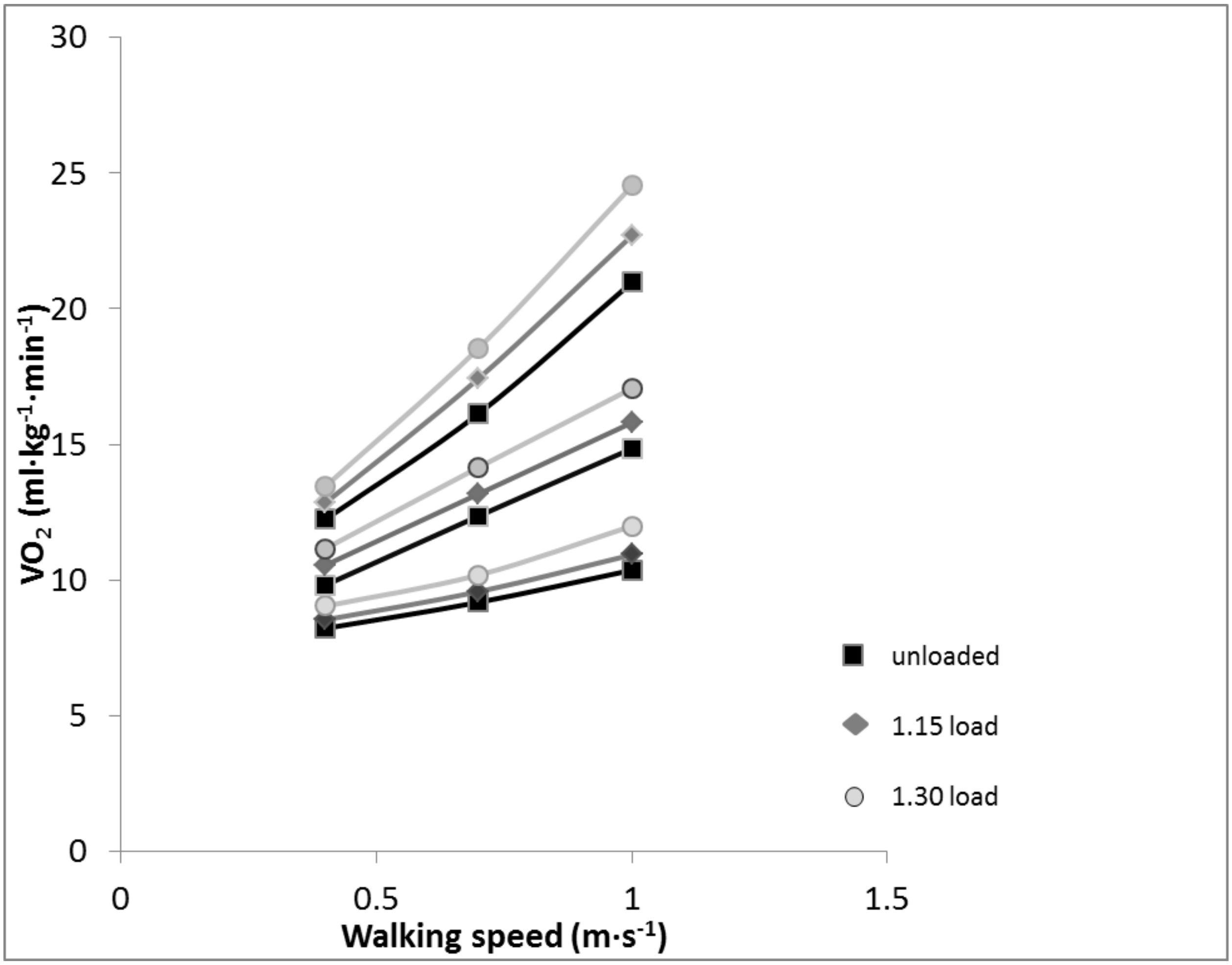


Figure 1. *Walking rates of oxygen uptake as a function of speed on three treadmill inclinations and under three loading conditions for one subject. All measures were taken under steady-state conditions.*

The vest and backpack selection were finalized in the latter portion of the prior reporting year once human subjects testing authorization had been acquired. The specific gear and loading schemes are illustrated in the pictures appearing in Figure 2:

Panel A

Panel B

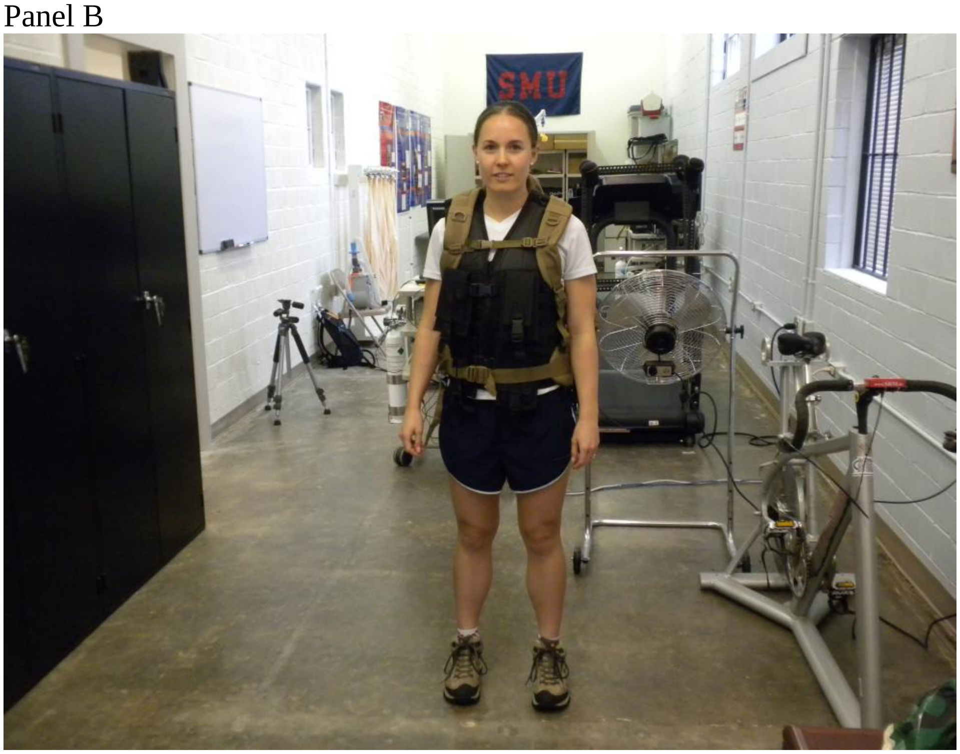
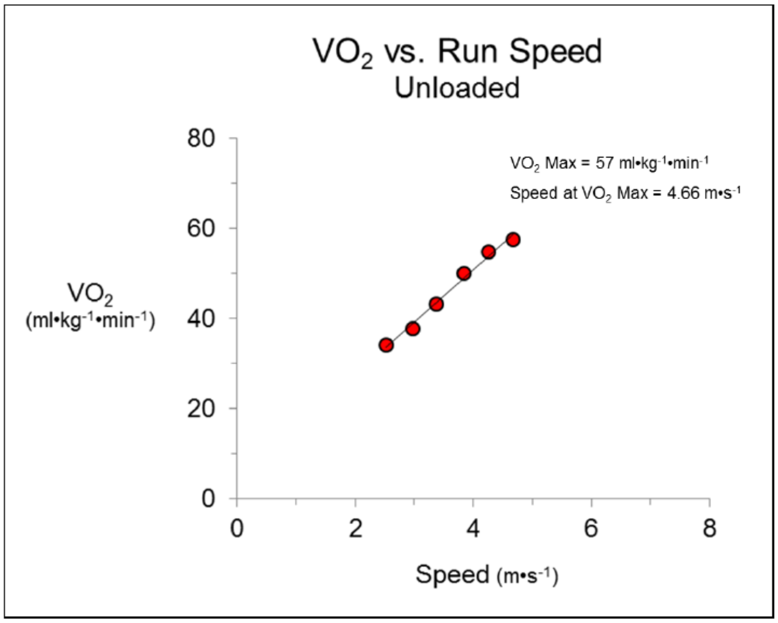


Figure 2. *The vest and backpack used to add loads to subjects from lateral (A) and front (B) views. Yoga blocks and sealed bags of shot are used to add the condition-specific weight needed for protocol administration for subjects who differ in body mass.*

In the first quarter, we also acquired initial data from our loaded running protocol for both the areobic demands of running under load and the performance-duration relationship for all-out runs of brief duration. Representative data from individual subjects appears below in Figure 3

Panel A



Panel B

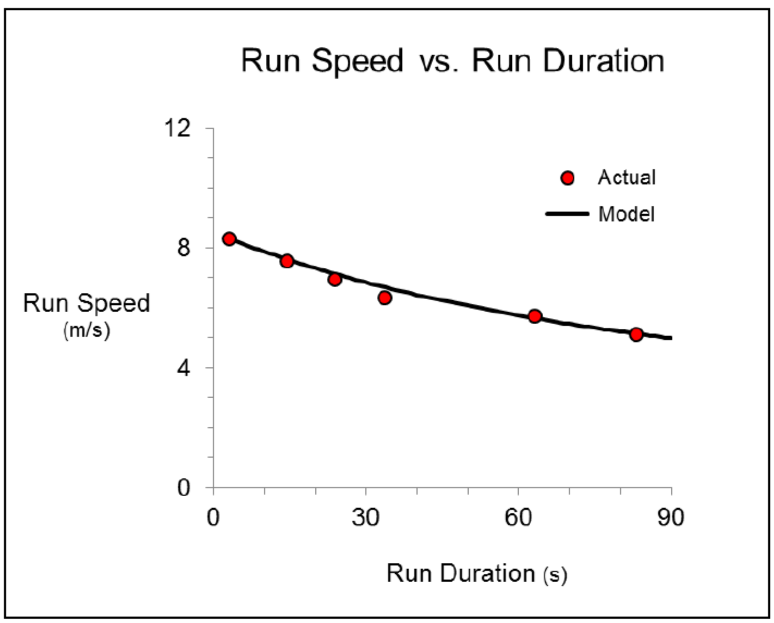


Figure 3. *Steady-state rates of oxygen uptake measured during a progressive, discontinuous treadmill test up to the individual's aerobic maximum in the unloaded condition (A) and all-out running speeds as a function of run duration while running also in the unloaded condition. The line depicts the predictions of the speed reserve model for performance under these conditions.*

In the second quarter of the last reporting year (July through September of 2013), our efforts focused primarily upon finalizing the experimental set-up and protocol for objective 1. As detailed in our quarterly report form this period, these efforts were:

1) Efforts were devoted primarily to testing and data acquisition, particularly to meet the very heavy testing and data acquisition requirements of objective 1 for predicting walking metabolic rates.
2) Testing protocols, weighting schemes and general logistics for the laboratory testing protocols were largely finalized. This included finalizing the protocol for the unloaded treadmill walking tests. Some modifications for the treadmill running tests came under consideration for refinement due to the rigor and number of test sessions involved for individual subjects.
3) Minor modifications were made to provide better padding of the backpacks for the walking sessions to make the subjects more comfortable during testing.
4) In preparation for the running biomechanics testing for objective 2, we purchased a motion capture system which has been delivered and is now up and running in our main laboratory. We prepared to begin validation of the new system against our existing system to ensure data validity.
5) Software programming to precisely locate the center of pressure on the force platforms to be used to running data acquisition was also initiated. The goal of these efforts was to resolve the location of the center of pressure on the force plates to within 1.0 millimeter or less. The estimated programming time requirement at this juncture was 80 hours.
6) We moved forward with site location and logistical preparations for the field test of the walking model.
7) We revised our running force model paper that was in review at the *Journal of Experimental Biology*.
8) Our manuscript that introduced a new generalized equation to predict walking metabolic rates was accepted and moved toward publication at the *Journal of Applied Physiology*.
9) We began an effort to digitize a literature data set to test and refine the walking metabolism model introduced in the paper currently in press.

Representative data for objective 2 on running metabolism are provided below in Figures 4 and 5 for both steady-state running at speeds below the aerobic maximum and for all-out running as a function of run duration on both the weighted and un-weighted conditions.

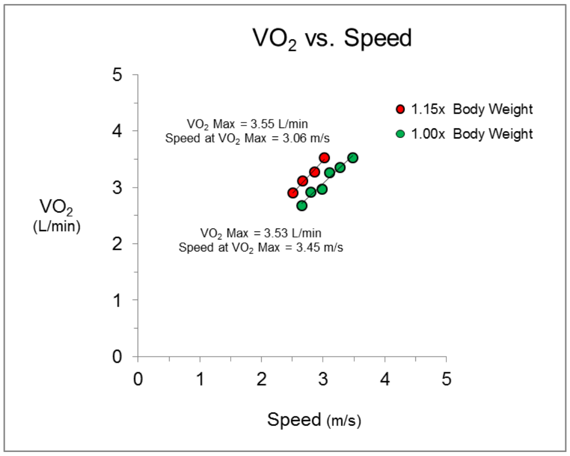


Figure 4. *Rates of oxygen uptake vs. speed during unloaded and loaded running.*

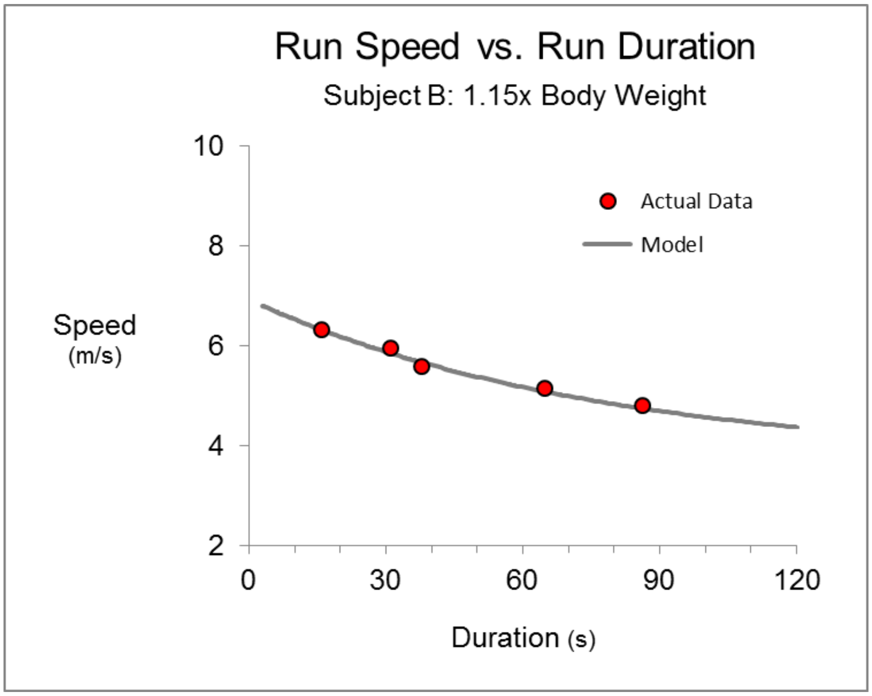


Figure 5, *All-out running speeds as a function of run duration during loaded running. The solid indicates the speeds predicted by the force-based speed reserve model as detailed in the grant proposal.*

In the third quarter of the last reporting period (October through December of 2013), as detailed in our January 2104 quarterly report, our efforts were as follows:

1) Continued testing and data acquisition, and technical efforts to set up data acquisition systems for objective two.
2) We also organized our efforts to organize and reduce data and conduct data analysis for both the walking (1) and running (2) objectives of the project.
3) Analysis and manuscript work continued in both the walking and running objectives.
4) Planning all aspects of the walking field tests also began. These include equipment, data acquisition systems, site planning and preparation, tec.
5) We made some modifications on specific test protocols for objective two on running mechanics to improve subject comfort.
6) Considerable effort was devoted to the technical work needed to ensure high quality mechanics data for grant objective two. These efforts included approximately 100 hours of software programming for precision location of the center of pressure on our contiguous in-ground force plates. This work was successfully completed. Per our last report, the resolution of the center of pressure on the force plates is 1.0 millimeter as anticipated. These efforts also included approximately 80 hours of system set-up and data acquisition testing using a new Opti-Track Motion Capture System procured to execute the experimental work on objective two.

7) We devised data reduction and organization systems for objective one on walking metabolism in order to allow for quick screening of the data upon acquisition. We also implemented a data organization system that will allow for rapid analysis and modeling with the large and unique metabolic data set we are in the process of acquiring.
8) We continued to refine our walking metabolism and running mechanics models with original and literature data. Several hundred person hours were devoted to both efforts in the last quarter. These efforts resulted in the submission of a revised manuscript on running mechanics to the *Journal of Experimental Biology* and a walking metabolism manuscript that is in preparation for submission to the *Journal of Applied Physiology*.

Per the report details presented in the report from January of 2014, we presented some of the data set and analysis of our digitized literature data set that was acquired to provide a robust, valid, level walking data set spanning a broad range of body sizes and a broad range of walking speeds. This data set includes original and literature data selected to maximize the natural biological variability present. The data set is comprised of mean data, with the subjects within each group being similar in stature, but with substantial height differences being present across groups. These data and preliminary analyses appear below in Figures 6 and 7.

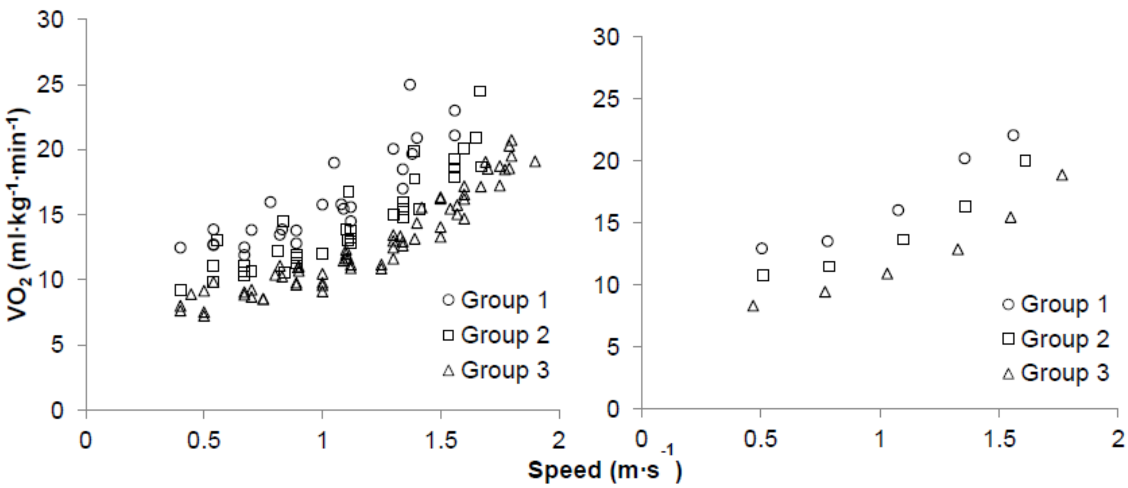


Figure 6. *Rates of oxygen uptake vs. speed during unloaded walking (panel A, n=129). Each data point represents the mean value acquired from a population of subjects walking on a firm level surface. The data set includes both over-ground and treadmill data. The three symbol types for group 1 (circles), group 2 (squares) and group 3 (triangles) are for short, medium and tall subjects. The overall* <u>*mean*</u> *values for all the subject groups within the three respective height ranges appear in panel B.*

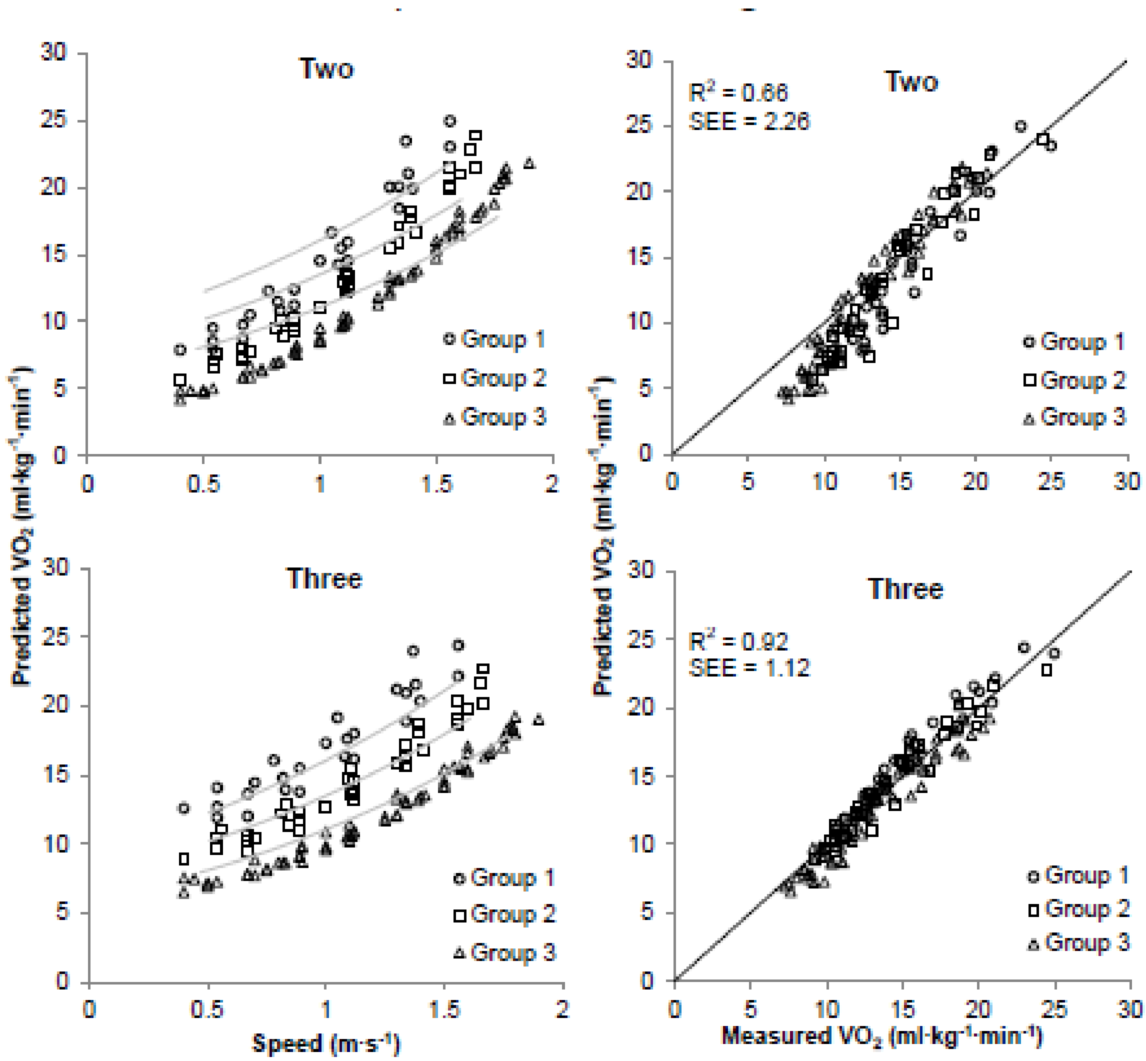


Figure 7. *Predicted rates of oxygen uptake vs. speed during level walking for groups of individuals who differ in height (left-hand upper and lower panels; circles- short, squares – average height, triangles – tall. The gray lines show the mean fits to the original data for each of the three height categories). The predictions are best-fit based on two iterations of our walking metabolism model, one with two metabolic components (upper left panel) and one with three metabolic components (lower left panel).*

Measured vs. model predicted values for these data points appear on the right-hand upper and lower panels labeled for two and three components, respectively. The proportion of variance accounted for has increased from prior reports, the predictive error has decreased and the error in the direction of prediction has become less sensitive to the absolute oxygen uptake values. [Note: the data points appearing correspond to the original data points from Figure 1, left-hand panel above].

In the final quarter of the reporting year (January through March of 2014), as detailed in our April 2014 reports, our efforts were as follows:

1) We nearly finished the data acquisition for the loaded portion of the treadmill walking protocol.
2) We began recruiting for the unloaded portion of the laboratory walking protocol.
3) Data analysis and manuscript preparation using a combined literature plus original data approach detailed in the last report continued. The objective of this effort has been to refine our height-weight-speed model of walking metabolism on level surfaces.
4) Preliminary modeling of the loaded treadmill walking data has begun.
5) Experimental planning and preparations for the field testing portion of objective 1 has continued. Refurbishing of our portable metabolic system was completed. A vertical and horizontal GPS system was purchased and acquired.
6) We completed preparations and begun pilot testing the biomechanics data acquisition system for objective 2. These efforts included force plate and motion capture data acquisition systems as detailed previously. These efforts required several hundred person hours during the last quarter. Briefly, the overground running mechanics technical efforts included custom programming of the force plate data acquisition system using LabView, configuring the OptiTrack motion capture system, establishing the marker set to be used for the testing (which would not interfere with the vest/backpack system), developing a custom start trigger method and pilot testing two subjects.
7) The treadmill running testing for objective 2 has continued.

Pilot and technical data from the extensive work done in the fourth quarter to set up, validate and pilot test the laboratory overground running data acquisition system t meet objective 2 apopears below in Figures 8 and 9.

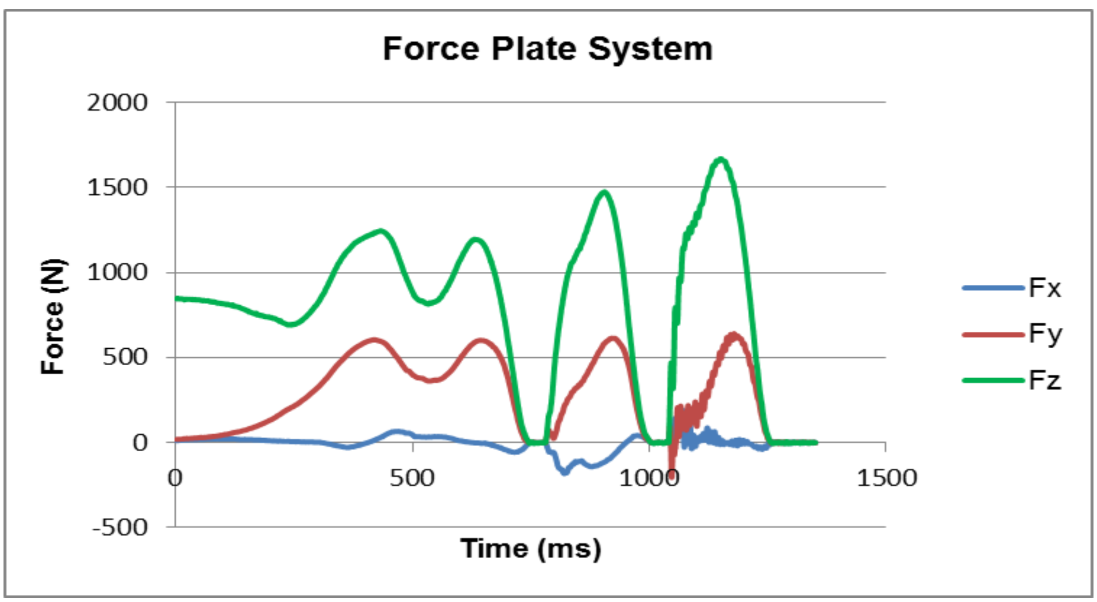


Figure 8. *Lateral (blue), horizontal (red) and vertical (green) ground reaction forces during an all-out run from a standing start through the second step two of a 10-meter running trial.*

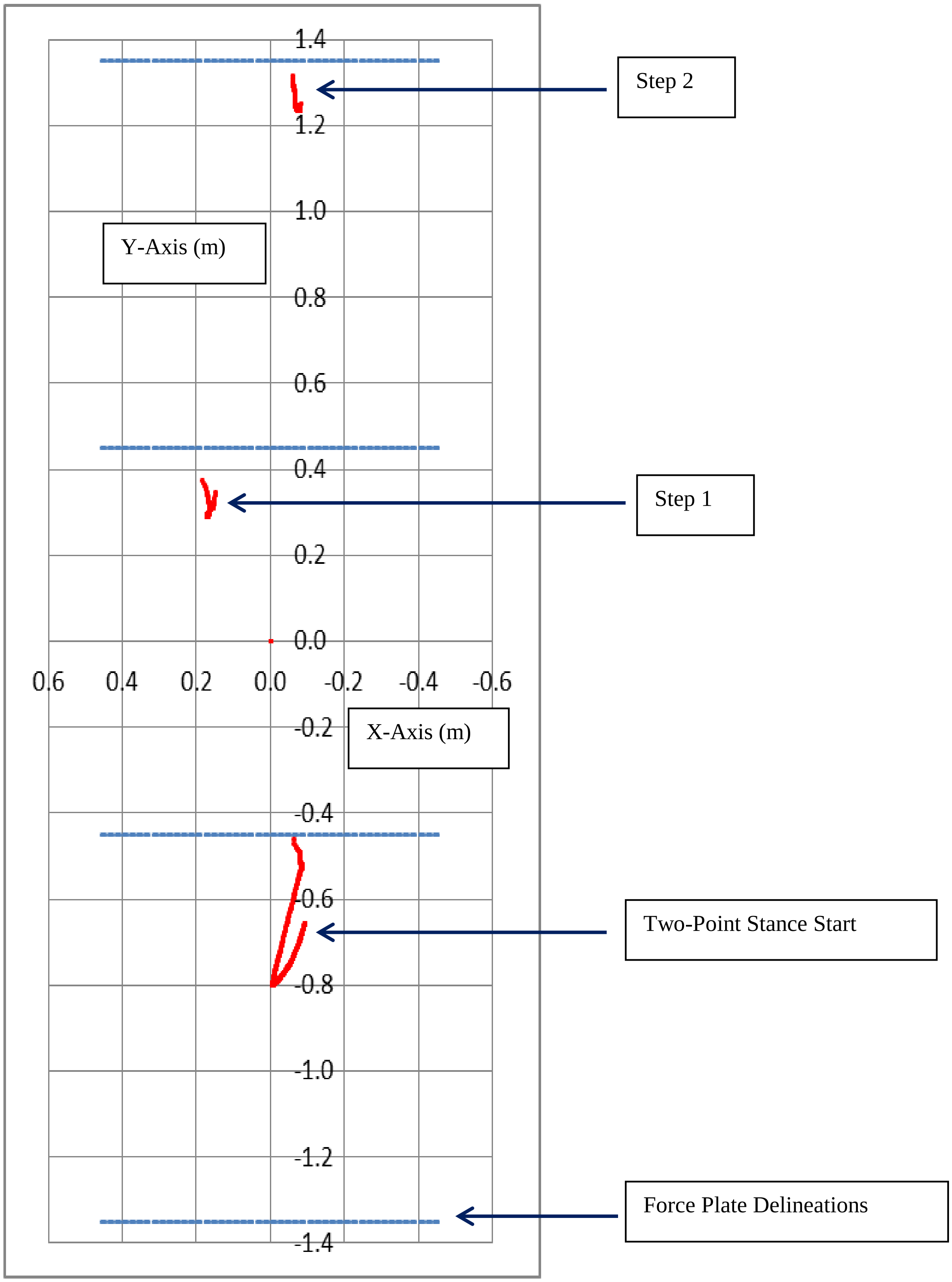


Figure 9. *Center of foot-ground pressure data from a standing start and the first two steps of a brief all-out run from our custom three-force plate system.*

REPORTABLE OUTCOMES

Reportable outcomes follow directly from the key accomplishments listed for each quarter above. These were:

1. We enrolled and tested 43 research subjects. Of these, 14 withdrew. Eleven of the withdrawals were voluntary, three were screen failures.
2. One hundred and eighty-eight test sessions were completed.
3. Nearly all of the loaded laboratory data acquisition for loaded walking was completed.
4. A portion of the loaded treadmill running data acquisition has been completed.
5. We have begun recruiting subjects for the unloaded portion of the treadmill walking protocol.
6. The data acquisition systems for the over-ground loaded running tests were set-up and validated. These preparations required hundreds of hours of technical work on force plate systems, motion capture systems, and timing systems.
7. The protocol for the loaded treadmill running tests has been modified to reduce the number fo test sessions required.
8. The elaborate preparations needed to undertake the field walking studies were begun. These have included the refurbishing of our portable metabolic unit, the identification of field site, the identification of a GPS system that provides both vertical and horizontal position data.
9. Two manuscripts were accepted for publication: one each in the *Journal of Applied Physiology* and *Journal of Experimental Biology*.
10. An additional manuscript on our walking metabolism is in progress.

CONCLUSIONS

In the second year of the award, we completed a substantial arduous work needed to set up and acquire data to meet the laboratory portion of the testing to meet objective 1 for walking metabolism. We also began running testing on the treadmill to meet the loaded running objective of the award. For the over-ground running portion of the project, we invested an enormous amount of labor in validating a new motion capture system against our existing custom system. The project is proceeding as envisioned and is expected to continue to be financially healthy and experimentally on track into the coming year.

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APPENDICES

Appendix 1. The Height-Weight-Speed Model and methods for acquiring and modeling level walking metabolic data from Weyand et al (2013).

The Height-Weight-Speed Model

Our three component model of walking metabolism is illustrated in Fig. 1. Rates of energy expenditure are illustrated as a function of walking speed, with the former expressed in units of oxygen uptake per physiological convention. Mass-specific rates of oxygen uptake typical for a tall adult appear on the left Y-axis while metabolic rates, expressed in multiples of the body's resting rate (METs), appear on the right Y-axis. The standardized values, theorized to apply to an individual of any height and weight, have been included to illustrate the model's postulated applicability across a broad continuum of human body sizes. The model partitions gross walking metabolic rates into three components: 1) resting metabolism, 2) minimum walking metabolism, and 3) speed-dependent walking metabolism. The scientific rationale for the model follows.
Resting Metabolic Rate (RMR): The model's first component is the minimum metabolic rate needed to supply all the body's tissues at rest, or resting metabolic rate. This component, in contrast to the other two in the model, can be directly measured under standardized conditions. For modeling purposes, we have assumed that resting metabolic rates accurately represent the minimum metabolic rate needed to sustain the body's tissues at rest and during exercise, and that this quantity is constant across different walking speeds.

Minimum Walking Metabolic Rate (MWMR): The model's second component is the minimum metabolic rate needed, above the body's resting rate, for walking at any speed. We have termed this component the minimum walking metabolic rate. The primary contributors to the minimum walking metabolic rate are the metabolic costs incurred to maintain an upright posture and support the body's weight against gravity in a walking posture. Secondary contributors include the slight elevations in cardiac and pulmonary muscle activity needed to support increased pulmonary oxygen uptake and cardiovascular transport, and perhaps other factors. For modeling purposes, we have assumed that the minimum walking metabolic rate, like resting metabolic rate, remains constant across walking speeds.

Speed-Dependent Walking Metabolic Rates (SDWMR): The model's third component is that portion of the gross walking metabolic rate attributable to walking speed. The primary contributor to this third model component is the increased metabolic cost of supporting the body's weight against gravity at faster walking speeds. This cost increases with speed as muscle fibers with greater rates of ATP utilization are recruited to support the body's weight during progressively shorter periods of foot-ground force application at faster speeds. Secondary contributors include performing the limited mechanical work per step required to lift and accelerate the body's mass, and the relatively small metabolic cost of swinging the limbs at faster walking speeds. Indirect evidence suggests that the two latter factors, although relatively small, do contribute to the increased slope of the metabolic rate-walking speed relationship across the fastest walking speeds.

Formulaic Basis of the Model: Of the three basic predictors in the Height-Weight-Speed model, the most straightforward influence is that of the total weight supported against gravity, which is typically the weight of the body. This direct influence is present in experimental results from load carriage studies, longitudinal studies involving weight loss, cross-sectional studies comparing obese and non-obese individuals, mechanistic explanations of locomotor metabolism and in the form in which body mass has been widely incorporated into existing predictive equations. All of the aforementioned experimental and predictive results are consistent with the conclusion that, when the other factors (height and walking speed) are held constant, a 1:1 relationship exists between the body weight supported and the metabolic energy walking requires. Hence, the widespread convention of expressing the metabolic rates observed during locomotion and other weight-bearing exercise in mass-specific terms enjoys extensive experimental support. Accordingly, we have incorporated body mass directly into all of the metabolic terms in our Height-Weight-Speed model as follows:

$$VO_{2\text{-gross}} = \underbrace{VO_{2\text{-rest}}}_{\text{Resting Metabolism}} + \underbrace{\underbrace{C_1 \cdot VO_{2\text{-rest}}}_{\text{Minimum Walking}} + \underbrace{(C_2 \cdot V^{exp}) \cdot Ht^{-1}}_{\text{Speed-Dependent}}}_{\text{Walking Metabolism}} \tag{1}$$

where $VO_{2\text{-gross}}$ is the body's total, or gross volume rate of oxygen uptake, $VO_{2\text{-rest}}$ is the body's resting rate of oxygen uptake, C_1 is a coefficient describing the minimum walking rate of oxygen uptake as a multiple of the resting rate, C_2 is the coefficient that describes speed-dependent increases in the rate of oxygen uptake as a function of the velocity of walking, V, raised to the exponent, *exp*, divided by the height, Ht, or stature of the individual. Hence, the sum of the model's second and third metabolic components represents the metabolic rate attributable to walking ($VO_{2\text{-walk}}$). To be consistent with prior literature, all the terms in Eq. 1 above are expressed in mass-specific units of oxygen uptake of mls $O_2 \bullet kg^{-1} \bullet min^{-1}$. Per our scientific objectives and both Fig. 1 and Eq. 1, the term metabolic rate is used to refer to mass-specific rates of oxygen uptake throughout the manuscript.

The quantitative form of the first of our model's three metabolic components ($VO_{2\text{-rest}}$, Eq. 1), the body's resting metabolic rate, is largely self-explanatory because resting metabolic rates are a standard and universally accepted measure. The second model component, the body's minimum walking metabolic rate, incurred predominantly by support and postural requirements, was assumed to be constant across speed at a fixed multiple of the body's resting metabolic rate ($C_1 \bullet VO_{2\text{-rest}}$, Eq. 1) largely on the basis of prior results. The most appropriate form for the model's third component, speed-dependent walking metabolic rate, is more difficult because the speed-induced increases in walking metabolic rates depend on stature (54). We postulated that the speed-dependent portion of walking metabolic rates would be an exponential function of velocity and an inverse function of height ($V^{exp} \bullet Ht^{-1}$) for the following reasons. First, both mechanics-based approaches and correlational modeling have been consistent in the finding that the increases in walking metabolic rates that occur with speed can be reasonably well described as a function of the velocity of walking squared. Second, among individuals who differ in body size, metabolic rate increases that occur with increases in walking speed are systematically greater in shorter vs. taller individuals, and therefore inversely related to stature. Hence, the model's third metabolic rate term takes the form of a coefficient times walking velocity raised to an exponent divided by height ($(C_2 \bullet V^{exp}) \bullet Ht^{-1}$, Eq. 1). In those instances in which *exp* has the theorized value of 2.0, this $V^2 \bullet Ht^{-1}$ term reduces to units of $m \bullet s^{-2}$.

Our model incorporates an existing solution for identifying speeds that are mechanically equivalent for individuals who differ in stature. This solution is derived from the principle of dynamic similarity, and has, in prior literature taken the form of the Froude number: $U = V^2 \bullet (g \bullet L_{leg})^{-1}$ where U is equivalent speed, V is the velocity of walking, g is gravitational acceleration, and L_{leg} is leg length. Our prior result at a single equivalent speed indicated that different-sized human walkers do indeed walk in a dynamically similar manner (54), which by definition entails stride lengths, times and forces being related to the body's linear dimensions by a constant across the full continuum of body sizes. In addition, we found that the energy cost per $kg \bullet stride^{-1}$ for shorter and taller individuals at the one equivalent speed examined did not vary. If our prior metabolic result from one equivalent speed generalizes to other equivalent speeds, then a single term that includes the walking velocity squared divided by the linear dimensions of the body should accurately describe the speed-dependent metabolic rates of different individuals regardless of their height. Here, for simplicity and ease of use, we used a Froude number analogue that replaced leg length with body length (i.e. height) and dropped the gravitational acceleration term to become: $V^2 \bullet Ht^{-1}$.

Our equivalent speed term for this third model component led us to two specific predictions. First, speed-dependent increases in mass-specific metabolic rates should be linear when expressed in relation to the velocity of walking squared. Second, the differences in how rapidly metabolic rates increase as a function of speed for shorter vs. taller individuals should be an inverse function of both leg length and height. Neither gender nor age were included in the model because both mechanical theory and prior empirical results (54) indicate these variables do not influence walking economy independently of height, weight and speed in healthy individuals under 50 years of age.

Experimental Protocol and Measurements

Subjects: Two strategies were employed to maximize the range of body sizes and walking metabolic rates obtained. First, we recruited human subjects who spanned a wide range of heights and weights. Second, we tested subjects across a nearly 5-fold range of walking speeds from 0.4 to 1.9 $m \bullet s^{-1}$. By recruiting children as young as five years of age and enrolling a number of individuals whose stature exceeded 2.0 meters (> 6' 6"), we obtained a nearly two-fold range of statures (1.07 to 2.11 m) and seven-fold range of body masses (15.9 to 112.8 kg) in our subject pool. We ultimately tested a total of 78 subjects, 45 males and 33 females, between the ages of 5 and 48 years. In accordance with local Institutional Review Board policies and procedures adults provided written informed consent while children provided written assent accompanied by the written consent of a parent or legal guardian. Subjects were healthy and generally free of obesity as only four of the 78 subjects had BMI values >30 $kg \cdot m^{-2}$. Limited data from 48 of the 78 subjects were reported in a prior study (54). Height and weight were measured with a stadiometer and platform scale accurate to the nearest 0.001 m and 0.1 kg, respectively. Leg lengths were measured by palpating the hip joint axis of rotation during standing and slow swinging of the limb in the sagittal plane.

Treadmill Testing Protocol: Subjects were asked to walk on a level treadmill at constant speeds of 0.4, 0.7, 1.0, 1.3, 1.6 and 1.9 $m \cdot s^{-1}$. The protocol began with a 4- to 6-minute walking trial followed by six trials at the aforementioned speeds. Each trial lasted long enough to obtain a 2-minute, steady-state rate of oxygen uptake. Speeds were administered in a staggered fashion beginning at 0.7 $m \cdot s^{-1}$. Subjects were given a 5- to 10-minute break after completion of the protocol before repeating all trial speeds a second time. Some of the shortest subjects did not complete trials at the fastest one or two protocol speeds because they could not do so without running.

Metabolic Measures: A computerized metabolic system (Parvo Medics TrueOne 2400, Sandy, Utah) was used to measure rates of metabolic energy expenditure as assessed from measured rates of oxygen uptake. Samples of expired gases during steady-state treadmill walking were taken and analyzed for CO_2 and O_2 fractions using infrared and paramagnetic gas analyzers, respectively. Respiratory gases were collected using a one-way breathing valve that directed expired air through a pneumotach into a mixing chamber before analysis. For each speed, rates of oxygen uptake were averaged over a two-minute, steady-state period and the steady-state values from the two protocol repetitions were averaged for subsequent data analysis. Calibration was performed using a three-liter syringe to direct air through the system at volume flow rates similar to ventilation rates encountered during testing. A two-point calibration procedure was used to calibrate the gas analyzers using room air and a gas cylinder containing known concentrations of O_2 and CO_2 in the physiological range for expired gases. The TrueOne system was also validated in the range of rates of oxygen uptake from 0.3 to 1.01 $liters \cdot min^{-1}$ via simulations using precision blended N_2–CO_2 mixtures according to the infusion technique described by Moon *et al*.. The agreement between the rates of oxygen uptake measured by the TrueOne system across 15 infusion tests spanning these simulated rates of oxygen uptake was < 3.0% as previously reported.

In previous work, we have converted measurements of oxygen uptake to metabolic rates or rates of energy expenditure using an energetic equivalent of oxygen of 20.1 Joules per ml of O_2. However, given the largely applied objective of the present study and existing literature conventions, here we report all results as rates of oxygen uptake (mls $O_2 \cdot kg^{-1} \cdot min^{-1}$) without conversion to true units of energy for ease of interpretation.

Kinematic Measures: Walking kinematics were obtained using a 30 Hz video (Sony model DCR-TRV19, 30Hz). Stride times (t_{str}) were determined by counting the frames of twenty-five sequential contact periods of the same foot. Stride time was defined as the time between successive footfalls of the same foot. Stride frequency, the inverse of stride time, was determined in order to quantify the energy expended per kg•stride as previously (54, where $E \cdot kg^{-1} \cdot stride^{-1} = VO_{2\text{-walk}} \cdot t_{\text{-str}}^{-1}$).

Appendix 2. Methods for linking running motion and vertical ground reaction forces

The Two-Mass Model

(a) Model Formulation

Because the net vertical displacement of the body over time during steady-speed, level running is zero, the time-averaged vertical ground reaction force must equal the body's weight. Thus, the total stance-averaged vertical force F_{Tavg} can be determined if foot-ground contact time t_c and aerial time t_a are known:

$$F_{Tavg} = mg\,\frac{t_{step}}{t_c} \tag{2.1}$$

where t_{step} is step time ($t_{step} = t_c + t_a$), m is body mass, and g is gravitational acceleration.

The ground reaction force waveform represents the instantaneous acceleration of the body's mass. Accordingly, the waveform can be conceptualized as the sum of the instantaneous accelerations of different segments that make up the body's total mass (Bobbert et al, 1991). In our model (figure 1), impulse J_1 results from the acceleration of the lower limb during surface impact, and J_2 corresponds to the acceleration of the remainder of the body's mass. The total impulse J_T, is the sum of J_1 and J_2:

$$J_T = J_1 + J_2 = F_{Tavg}\,t_c \tag{2.2}$$

Impulse mass m_1 is the 8.0% of the body's total mass attributed to the lower limb, while impulse mass m_2 is the remaining 92.0%. Impulse J_1 is quantified from the deceleration of m_1 during surface impact:

$$J_1 = F_{1avg}\,(2\,\Delta t_1) = m_1\left(\frac{\Delta v_1}{\Delta t_1} + g\right)(2\,\Delta t_1) \tag{2.3}$$

where Δt_1 is the time interval between touchdown and vertical velocity of m_1 slowing to zero, Δv_1 is the change in vertical velocity of m_1 during Δt_1, and F_{1avg} is the average force during the total time interval ($2\Delta t_1$) of impulse J_1. Impulse J_2 is determined from J_1 and total impulse J_T as:

$$J_2 = J_T - J_1 = F_{2avg}\,t_c \tag{2.4}$$

where F_{2avg} is the average force of J_2 during the interval t_c.

(b) Modeled Waveforms

The bell-shaped force curves $F(t)$ for J_1 and J_2 are a result of non-linear elastic collisions (Cross, 1999) that can be accurately modeled using the raised cosine function:

$$F(t) = \begin{cases} \frac{A}{2}\left[1+\cos\left(\frac{t-B}{C}\pi\right)\right] & for\ B-C \le t \le B+C \\ 0 & for\ t < B-C\ and\ t > B+C \end{cases} \quad (2.5)$$

where *A* is the peak amplitude, *B* is the center time of the peak, and *C* is the half-width time interval. Due to the symmetrical properties of this function, peak amplitude $A = 2 F_{avg}$, and the area under the curve is $J = AC$. The total force waveform $F_T(t)$ is the sum of each impulse waveform:

$$F_T(t) = \frac{A_1}{2}\left[1+\cos\left(\frac{t-B_1}{C_1}\pi\right)\right] + \frac{A_2}{2}\left[1+\cos\left(\frac{t-B_2}{C_2}\pi\right)\right] \quad (2.6)$$

A_1 is calculated from F_{1avg} using the Δv_1 and Δt_1 terms in equation 2.3, and B_1 and C_1 equal the time Δt_1 after touchdown for the vertical velocity of m_1 to reach zero. A_2 is calculated from F_{2avg} in equation 2.4, and B_2 and C_2 equal one-half the contact time t_c.

(c) *Modeled vs. Actual Waveforms*

We digitized (Engauge, version 4.1) four published waveforms that varied in duration, amplitude and shape (table 1). Model fits of the four digitized waveforms (figure 2) were performed via a manual iterative process that constrained the inputs for Δt_1 and Δv_1 to values deemed realistic on the basis of existing literature. Inputs for t_c and subsequent t_a were determined using a threshold of 60 N. In two cases (waveforms 3 and 4), goodness of fit between modeled and original data waveforms were determined to supplement the evaluation of the digitized versions.

Model fits were quantified in two ways: 1) in force units standardized to the body's weight (W_b) using the root mean square statistic (RMSE), and 2) for goodness of fit using the R^2 statistic. Digitized waveforms were interpolated as needed to provide force data on a per millisecond basis for these analyses. We hypothesized that the model would explain 90% or more (i.e. $R^2 \geq 0.90$) of the force-time variation present in each of the four of the waveforms analyzed. Data for all digitized, modeled and original waveforms used in the analysis are provided in the electronic supplementary material.

All variables are presented in MKS units, but, per convention, force waveforms are illustrated in mass-specific units.