SPEED VARIATION AND POWER TRANSFER DURING TREADMILL RUNNING

INTRA-STEP BELT-SPEED VARIATION AND HORIZONTAL POWER TRANSFER DURING TREADMILL RUNNING

By

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Abstract

The motor driven treadmill is often used in research as a convenient tool for simulating overground running. There has been varied opinion in the literature regarding the accuracy of this assumption. The major difference that has been quantified is the variation in treadmill belt speed as a result of the forces applied by a runner. In comparison, the earth does not vary its speed during overground running. The aim of the present study was to more clearly define the causes of treadmill belt-speed variation and to elucidate its effects on running mechanics.

An in-lab fabricated tachometer was used to determine accurate treadmill belt speed while the treadmill was challenged by five subjects weighing 55.2 to 99.6 kg running at four speeds of 2.6, 3.1, 3.5 and 4.0 m/s. The actual running velocity was found on average to be 0.62 % higher than the treadmill display setting. The intra-step belt-speed variation ranged from 4.2 to 8.6 % of average belt velocity. Linear regression analysis showed that 86 % of the variance in intra-step belt-speed variation was attributed to total body mass and a further 10 % attributed to running speed.

The effect that this variation had on running mechanics was determined from the power transfer between the foot and belt, as calculated from the product of the change in belt speed and the horizontal ground reaction force. The horizontal force, as calculated using a segmental acceleration approach, did not show complete agreement with simultaneously recorded forceplate data. It was found that an average of 4.49 J flowed to the treadmill during the eccentric phase of running and 3.37 J of energy flowed to the runner during the concentric phase of running. Despite inaccuracies in the calculation, the mathematical approach used in this study permitted insight into the theoretical benefit of belt-speed variation in treadmill running.

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Chapter 1

Introduction

The motor driven treadmill is often used in research to analyze biomechanical and physiological aspects of locomotion in training and rehabilitation. This enables researchers to collect data on a standardized and reliable performance task and then generalize the results to overground locomotion. There is, however, varied opinion in the literature regarding the comparability of values from these two events. The most widely accepted difference between treadmill and overground running is the fluctuation in treadmill belt velocity within each stride. As a result, there has been a recent effort to determine the parameters that cause this fluctuation as well as the implications this fluctuation has on treadmill kinematics and energetics (Schamhardt et al, 1994; Savelberg et al., 1998; Radstake and Dowling, 1999).

Some of the parameters that have been shown to affect the extent of treadmill belt fluctuation include the power of the treadmill motor, the friction between the belt and treadmill bed, and the subject's mass, running speed and running style. The first purpose of this study was to use an in-lab fabricated tachometer to determine instantaneous belt velocity while the treadmill was being challenged by subjects, with a wide range in body mass, running a wide range of speeds. A multiple linear regression analysis was performed to demonstrate the dependence of intra-step treadmill belt-speed variation on these parameters. This calculation of treadmill belt velocity also provided insight into the actual speed the runner was travelling in order to compare to the speed setting indicated by the treadmill.

In order to truly understand the reasons why fluctuations in belt velocity occur, all the interacting forces that cause these fluctuations need to be quantified. This is not an easy task. Van Ingen Schenau (1980) compared overground and treadmill running using a theoretical model to show that the mechanics are the same as long as the motorized treadmill is powerful enough to produce a constant belt speed. Despite the fact that fluctuations in treadmill belt velocity have proven inevitable, the effects of velocity fluctuations on mechanical power and energy calculations have rarely been quantified. The major reason cited for this neglect is the cost and difficulty involved in elucidating the power fluctuations of the treadmill motor.

Another challenge of the treadmill power calculation lies in the use of the proper frame of reference so that sensible values are achieved which explain the difference between treadmill and overground running. As the subject pushes against the ground, an energy flow to the earth can only occur if the surface is displaced at the point of contact, as in the case of walking on soft surfaces, like sand. Likewise, on a treadmill, if the belt yields to the forces applied by a runner, an energy flow occurs at the foot/belt node. In contrast, on any hard surface, any acceleration of the ground resulting from the ground reaction force can be neglected on the basis of the mass difference between the subject and the earth (Webb et al., 1988). In order to maintain average velocity overground, the subject needs to concentrically push-off against the ground to produce positive work equal in magnitude to the negative work of absorption in early stance. In treadmill running, however, the equal portions of negative and positive work may be achieved partly by the runner, and partly by the treadmill.

A second purpose of this study was to determine the energy flow between a runner and the treadmill belt at the foot-belt interface. The power transfer of the subject was determined by the horizontal force produced multiplied by the change in velocity that occurs at the point of transfer. Although the horizontal force can easily be determined during overground running on a force platform, no such solution exists for treadmill running. Instead, the external force applied by the subject to the treadmill was determined by the acceleration of the whole body centre of mass, as determined by double differentiation of segmental marker position data multiplied by the subject's mass (Bobbert et al., 1991). The measurement of the belt velocity was used as an accurate measure of the foot's velocity assuming negligible slippage of the foot within the shoe or the shoe on the belt. It was hypothesized that significant fluctuations in velocity would indeed be observed which would result in power transfers between the runner and treadmill belt that do not occur overground. These horizontal power transfers might be analogous to the vertical considerations on track compliance of McMahon and Greene (1979).

Chapter 2

Review of Literature

Kinematic and energy cost discrepancies have been found between treadmill and overground locomotion. However, because of the many interdependent variables, the treadmill versus overground results are inconsistent and include differences in step length, step frequency and contact time (Frishberg, 1983; Nelson et al., 1972; Wank et al., 1998) as well as differences in energy cost (Frishberg, 1983; Pugh, 1971; Wank et al., 1998). Directed by this kinematic and physiologic framework, there has been recent interest in treadmill kinetics and mechanics which may help explain some of these findings.

2.1 Treadmill Kinematics

A good overview of treadmill versus overground kinematics was presented by Nigg et al. in 1995. This group suggested that the inconsistent findings in the literature might be related to the different types of treadmills used. They speculated that larger, more expensive treadmills offer a better driving mechanism and better perceptual information so as to reduce the differences in running style between treadmill and overground running.

There is some evidence that treadmill running is characterized by longer stance periods and shorter flight phases. Nelson et al. (1972) found longer periods of support at

6.40 m/s, and lower and less variable vertical velocities and less variable horizontal velocities at treadmill running speeds of 3.35, 4.88 and 6.40 m/s compared to similar overground speeds. Wank et al. (1998) also reported a reduction in vertical displacement and vertical and horizontal velocity variation as well as an increase in forward trunk lean and stride frequency and a decrease in step length during treadmill running at 4.0 to 6.0 m/s. This group acknowledged that the kinematic differences between treadmill and overground running they found could have been the result of variation in treadmill belt velocity which was not monitored in their study. Other studies have reported similar findings for middle-distance running speeds and at speeds of 3.3 m/s to 4.8 m/s on the treadmill (Dal Monte et al., 1973; Elliot and Blanksby, 1976). Frishberg et al. (1983) found that the leg of the supporting lower extremity was less erect at contact and moved through a greater range of motion at average sprinting speeds of 9.2 m/s. In general, it seems that differences that have been found point to a secure running strategy which emphasizes movement in the horizontal direction as opposed to the vertical direction.

2.2 Treadmill Energetics

The aim of energy analyses on elite athletes is to determine minor alterations in movement pattern to improve performance by a few percent. It has been suggested, however, that differences between treadmill and overground running are in excess of these minor alterations (Winter, 1978). In general, the net energy consumed during an activity is dependent on the level of mechanical work that is done. The relationship between energy expended and work done is termed "efficiency". The greater the amount of work done for a given amount of energy expended, the greater the efficiency. Likewise, the less energy that is expended to perform a given work load, the better the efficiency. Submaximal, steady-state oxygen consumption (VO_2) is generally accepted as the global measure of metabolic energy cost of an activity (Daniels, 1985). It is much more difficult to determine an accurate measure of the corresponding mechanical work that is being done since it is highly dependent on the assumptions made with regard to definitions of internal and external work, energy transfers and relative efficiencies of positive and negative work (Pierrynowski et al., 1980; Kaneko, 1990). The many different ways to calculate the energetic costs and corresponding mechanical work are beyond the scope of this study. However, for the purpose of drawing comparisons between treadmill and overground running, it is often assumed that the mechanical work is similar and therefore, differences in the energy cost alone are reported with respect to running velocity. This measure is referred to as running "economy".

In practice, the stationary treadmill has distinct advantages for collection of metabolic and cardiorespiratory recordings used for energy cost estimation in elite long- and middle-distance runners (Wank et al., 1998). However, it is generally accepted that the treadmill belt does indeed slow down as a result of the load of a person, so the speed at which the treadmill is set is likely an overestimation (Cavanagh and Williams, 1982). To account for this error, the actual average speed on the treadmill has been calculated by timing 15 - 25 revolutions of the belt (Bassett et al., 1985; Bourdin et al., 1993; Lacour et al., 1991). Optical encoders have also been used to determine close to instantaneous belt speed via average velocity between closely spaced reflectors on the belt (Bourdin et al., 1995). In order to match this speed when running over the force plate, optical sensors are used to calculate average velocity within the proximity of the force plate, and trials are only accepted if the overground velocity matches the treadmill velocity within, for instance, +/- 0.05 m/s (Wank et al., 1998).

Studies since the 1950's support a linear or very nearly linear relationship between running speed and VO_2 in ml/min/kg. The reported differences in the economy of overground and treadmill running depend on the velocity of running. McMiken and Daniels (1976) found no differences between the oxygen demand of level treadmill and overground running at speeds between 3.0 m/s and 4.3 m/s. Indeed, numerous studies in the 1970's compared the energy expenditure of overground and treadmill running and little difference was found for speeds below 4.5 m/s (Frishberg, 1983). However, Pugh et al. (1970) reported slightly greater VO_2's at 6.0 m/s, with air resistance being suspected as the major contributor. Pugh's group also found a 15 % increase in submaximal VO_2 when a 4 m/s headwind was created during treadmill running to simulate outdoor conditions. They calculated the energy cost of overcoming air resistance to be up to 7.5 % of the total energy cost of middle distance races.

At maximal sprinting velocities for the 100 yd dash, Frishberg (1983) found the oxygen debt of overground sprinting to be 36 % greater than that for treadmill sprinting at incremental velocities corresponding to the overground condition. This deviation was larger than could be explained by air resistance alone so it was suggested that the moving treadmill belt reduced the runner's energy requirement by bringing the support leg back under the body.

2.3 Treadmill Velocity

In recent years, there has been an effort to quantify the magnitude of treadmill belt speed variation. Since there are no ground speed variations during overground running, it is anticipated that this parameter may offer insight as a source of different kinematics and energetics. A number of treadmill and subject factors affect the reported magnitudes of belt velocity fluctuations. Treadmill parameters include the power of the treadmill motor, the friction between the belt and treadmill bed, the tension on the belt, and the speed at which the treadmill is set. The subject's mass and running style (rear- vs mid- vs fore-foot contact) also affect the magnitude of variation (Savelberg et al. 1998; Calame, 1998). Values of intra-stride belt-speed variation range from 2 to 14 % for a variety of conditions (Frishberg, 1983; Webb et al., 1988; Schamhardt et al., 1994; Savelberg et al. 1998; Calame, 1998; Radstake and Dowling, 1999).

The first study that focused directly on this issue was performed on horses. Schamhardt et al. (1994) investigated velocity fluctuations of a high powered (22 kW) treadmill belt with five horses trotting at 4 m/s. Instantaneous velocity, as obtained by integrating accelerometer data from the hoof, was minimal at mid-stance, and maximal at lift-off. There was a 12% variation in velocity for a 740 kg horse which decreased linearly to about 7 % for a 475 kg horse. For comparison, a 72 kg human subject also ran on the treadmill at 4 m/s resulting in a belt speed variation of only 3%. It was expected that much larger variations would be observed on a much less powerful treadmill designed for human use. Indeed, this was the case as shown in follow up research by this group. Savelberg et al. (1998) reported values of 3 to 6 % as obtained by the first order derivative of a marker placed on the belt. It was found that treadmill power accounted for 55 % of the variance in intra-stride belt-speed variation while different subject masses accounted for another 7.5 %. The two treadmills used in this study differed greatly in power (3.4 kW vs 22 kW) which explains the high dependence of intra-stride belt-speed variation. The two speeds of locomotion, one walking and one running did not contribute significantly to the variance. Of course, intra-stride belt-speed variation is already expressed as a percent of belt speed, which indicates that the absolute value of variation did increase with increasing speed. Although this study presents the most extensive investigation into velocity fluctuation, they note that lack of discriminative power in the experimental design prevented an effect for speed of locomotion.

The Gaitway™ instrumented treadmill from Kistler calculates instantaneous belt velocity in order to determine center of pressure on the force plate. Based on subjects walking on this treadmill at 0.83 and 1.11 m/s, belt velocity tended to vary between 2 and 5 % of belt velocity (Calame, 1998). In data from our lab, belt velocity was shown to vary 9.4 % of average velocity for a 70 kg subject running at both 2.68 and 3.22 m/s and 12.9% and 14.3%, respectively, for a 104 kg subject running at the same velocities on a Woodway treadmill (Radstake and Dowling, 1999). The trends in these data suggest that the range of velocity fluctuation are dependent on the type of treadmill, the runner's mass and the runner's velocity.

2.4 Treadmill power

To delve further into the subject, the questions are raised about the effect of these treadmill belt speed fluctuations on the energetics of running. Elucidating the cause has not been a trivial task, as evidenced by a summary of responses to a Biomechanics and Movement Science listserver posting (Dowling, 1995). Some researchers had attempted to quantify the power drawn by the motor but have been unsuccessful as a result of extraneous factors such as belt slippage and frictional losses between the treadmill bed and belt. The most promising method for elucidating the power transfer between the treadmill belt and a runner's foot seemed to be the product of the interacting force in the horizontal direction and the resulting change in velocity. The major challenge of this methodology is the quantification of the horizontal foot/belt force.

Studies to date have used a corresponding ground reaction force obtained during overground running for use in the power calculation (Shamhardt et al., 1994; Savelberg et al. 1998). Schamhardt et al. (1994) calculated the power transfer between the treadmill belt and the horses by using overground fore-aft GRF data with treadmill velocity fluctuation data. The power transfer increased more or less linearly from about 20 to 74 W with five body masses between 475 to 740 kg and also from 28 to 106 W when the speed was increased from 2.6 to 5.0 m/s. Savelberg et al. (1998) estimated the peak power to be 10 W from the runner to a lower powered treadmill and 10 W to the runner on a high powered treadmill. It is noted that these power estimates are sensitive to the chosen frame of reference for the velocity. Therefore, the time integral of power (work) may be a more valid measure. The estimated absolute energy flow while running 2.3 m/s was 1.4 J/stride on the low powered treadmill and 1.0 J/stride on the high powered treadmill.

Recent advancements have made it possible to incorporate force platforms within the bed of the treadmill such as the Gaitway™ instrumented treadmill (Kistler Instrumente AG Winterthur, Switzerland) and that used by White et al. (1998). Although this is an extremely expensive option, it allows metabolic cost and mechanical work estimates to be collected on precisely the same event; treadmill locomotion. More importantly for the present discussion, this treadmill can only determine vertical forces since the movement of the belt over the force platform prevents the calculation of horizontal forces. Solutions to this problem are in the developmental stage at this time.

Without a means of determining the forces on the body while on a treadmill, researchers have attempted to quantify the observable accelerations that these forces cause. Belli et al. (1993) and Bourdin et al. (1995) have used a kinematic arm to obtain an estimate of the CM movement. The kinematic arm consisted of four rigid bars link together with optical encoders at each joint which determine the angle between the bars. One end of the system was attach to the fixed frame of reference and the other was attached to a runner's waist. This device was used to calculate the instant position of the approximate centre of mass for use in external mechanical work calculations. They reported a 1.4 +/- 1.8 % difference in these work calculations using the kinematic arm as compared to a force platform. This study collected the raw data that would be required for a treadmill power transfer calculation but it was not reported.

Alternately, Bobbert et al. (1991) showed that positional data of all body segments can be sufficient to calculate the inter-segmental forces that make up the vertical ground reaction force. They used a seven segment model, attached markers to light wooden rods on the legs to fix the lengths of these segments and filtered lower limb data at 50 Hz, the hip data at 20 Hz, and the chest and head data at 15 Hz to obtain their signal. They were able to estimate the magnitude of the high frequency impact force during running with errors of less than 10 % and the time of occurrence of that spike with errors of less than 5 ms. This procedure has not been extrapolated to horizontal forces.

Yet another way to determine this power transfer was achieved by the measurement of heat. Since work is strictly defined as "force expressed through distance, or energy transferred from a man to the environment, but not as heat" (Webb et al., 1988), Webb used oxygen consumption and calorimetry to determine that more energy was consumed than the amount of heat produced from internal work, meaning that work was done in level walking between 2.5 and 6.7 km/hr (0.69 - 1.86 m/s). This external work was theorized to arise from compression of the heel of the shoe and bending of the sole. Given mean deceleration and propulsion forces of approximately 10% of body weight at a walking speed of 7.2 km/hr and the velocity fluctuations they found, a maximum energy flow of only 6 W was estimated.

Chapter 3

Methods

3.1 Subjects

Five physically active males with some previous treadmill running experience volunteered to participate in this study. An attempt was made to approach potential subjects that represented a large range in total body mass. Subject characteristics are listed in Table 1. All participants were informed about the experimental protocol and signed a consent form.

Table 1 Subject Characteristics

Subject	Age (yrs)	TBM (kg)	Height (m)	BMI (kg/m^2)
1	23	55.2	1.63	20.8
2	22	66.7	1.58	26.7
3	24	77.7	1.78	24.5
4	25	89.3	1.75	29.2
5	25	99.6	2.00	24.9
Average (+/-sd)	23.8 (1.3)	77.7 (17.6)	1.75 (0.16)	25.2 (3.1)

TBM = Total Body Mass; BMI = Body Mass Index; sd = standard deviation

3.2 Experimental Protocol

Subjects were first instructed to familiarize themselves with the treadmill by considering the following requirements: a consistent running pattern for short periods at speeds up to 4.0 m/s followed by hopping off the side of the treadmill with the use of the front hand rail. All subjects were able to perform the requirements without undue stress.

Ten infrared emitting diode (IRED) markers were placed on the following joint centres: left and right metatarsal-phalangeal, ankle, and knee, the right hip, right wrist, right elbow and on a lock on the seventh cervical vertebrae. In order to collect data from the right sagittal plane, markers on the right extremities were attached to the lateral aspect of the joints while the left side markers were attached to the medial aspect of the joints. Three additional markers were attached to the right heel, right toe and left heel for the purpose of fragmenting data into consecutive steps. Markers were connected to a strober unit attached to a belt around the subject's waist. Refer to Figure 1 for a schematic of marker placement.

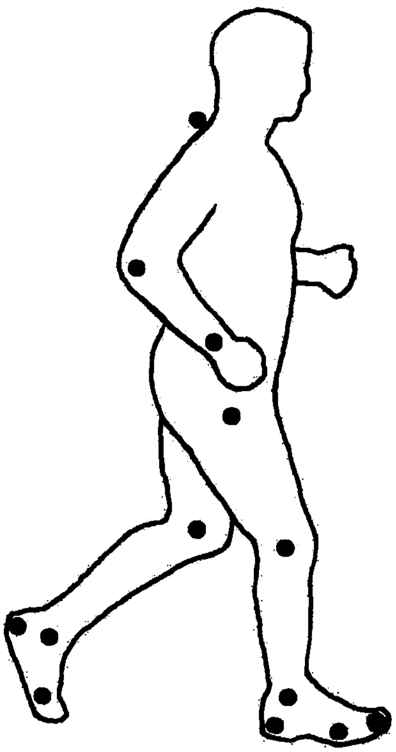

Figure 1. IRED Marker Placement

Measures of height and total body mass including the marker apparatus were recorded as indicated in Table 1. Subjects ran at four different speeds corresponding to treadmill speed settings of 6, 7, 8, and 9 mph (2.7, 3.1, 3.6, 4.0 m/s) in randomized order. Once the subject displayed a consistent running pattern, data was collected for ten seconds. Following this, the subjects dismounted and an identical collection of treadmill belt velocity was made at the same setting without the runner.

For the purpose of validation of the horizontal force on the runner (F_x), as calculated using inverse dynamics during treadmill running, additional trials were performed while running overground on a runway equipped with a force platform (AMTI model OR6-5, Advanced Mechanical Technology, Inc., Massachusetts, USA). Force platform and marker data were collected simultaneously at a variety of speeds within the range of treadmill running speeds, as approximated by a stopwatch. Subjects were asked to indicate the treadmill speed that they felt most closely corresponded with the overground trials.

3.3 Data Collection

Marker movements were sampled at 120 Hz using an optoelectronic three-dimensional motion measurement system (OPTOTRAK/3020, Northern Digital, Inc., Waterloo, Canada). The camera unit was positioned vertically and at a right angle to the subject's sagittal plane at a distance of 5 meters from the treadmill and 6 meters from the force platform.

The treadmill used in this study was the True SOFT step (15 Amp) to which an in-lab fabricated tachometer was attached at the front corner of the belt for calculation of instantaneous belt velocity. The tachometer consisted of a hard rubber wheel (circumference 239.5 +/- 0.167 mm) attached to a continuous output potentiometer with 0.1 % linearity. Refer to Figure 2 for an illustration of the device. The continuous rubber belt of the treadmill

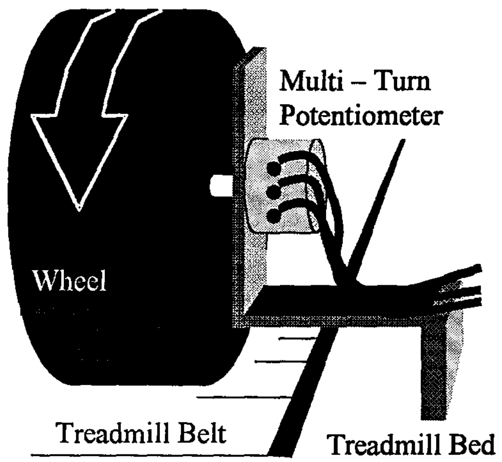

Figure 2. In-Lab Fabricated Tachometer for the Measurement of Instantaneous Belt Velocity

was tightened on the rollers in order to reduce slipping or stretching as a result of forces applied by the runner. A preliminary data collection was performed on a 80 kg subject running at 4.0 m/s with the tachometer placed at the front and then in the middle of the belt. The results showed consistency between the two measures of velocity suggesting that belt stretch was not a significant issue and therefore the instantaneous belt velocity under the stationary node at the front corner of the belt was an adequate prediction of the instantaneous velocity of the node under the moving foot.

Ground reaction forces and moments were registered through a multi-component force platform. Both tachometer and force platform data were sampled at 1200 Hz and channeled to an OPTOTRAK Data Acquisition Unit (ODAU) for A/D conversion (12 bit). Marker data were synchronized with the tachometer for the treadmill trials and with the force platform for the overground trials using a the ODAU (OPTOTRAK Data Acquisition Unit) and an IBM compatible, pentium personal computer.

3.4 Data Processing

Three dimensional marker co-ordinates, tachometer voltages, and force platform voltages from the OPTOTRAK system were converted to ASCII files for processing. Various QuickBASIC programs were created or modified from existing lab programs to aid in the procedure. For co-ordinate data, the x-axis defined the horizontal direction and the y-axis defined the vertical direction, with positive directions anteriorly and superiorly, respectively. Of the three dimensional data, the x-axis was the only dimension used in the analysis of the horizontal ground reaction force while the y-axis data from heel and toe markers were used for event identification. Loss of marker data occurred as the left leg passed behind the right leg as well as from periodic electrical interference from the treadmill. These missing data were successfully interpolated using cubic spline estimation. All co-ordinate, tachometer, and force platform data were filtered using a dual-pass, critically damped, low-pass filter with a cutoff frequency of 10 Hz. This cutoff frequency was used for running by Savelberg et al. (1998) and was also chosen as a conservative value based on expected signal frequencies below 5 Hz.

3.4.1 Event Identification

The second derivative of y-co-ordinate data from the right heel, right toe and left heel were used to identify the events of contact. Right heel contact (RHC), right toe off (RTO), and left heel contact (LHC) were identified by sharp, positive inflections of the acceleration data. The overground trials granted an opportunity to validate this event identification procedure. These events were used in order to obtain an ensemble average of right stance phases (RHC to RTO) and right step phases (RHC to LHC). The first frame included in each stance or step phase was the frame immediately preceding the RHC event and the average number of frames before RTO or LHC was used for each trial to facilitate the ensemble averaging process. Based on data from an independent study (Radstake & Dowling, 1999), it was known that at least 12 steps would be recorded for all subjects within the ten seconds of collection.

3.4.2 Treadmill Belt Velocity

First of all, the varying of terminology between velocity and speed should be qualified. The velocity term is used here to distinguish the measured speed from the treadmill speed setting, even though the treadmill belt velocity is given as a magnitude only for the velocity analysis. The vector quantity (magnitude and direction) is, however, required in the analysis of kinetic energy and treadmill power in sections 3.4.5 and 3.4.6, respectively.

The data obtained from the tachometer was processed according to a previous study (Radstake and Dowling, 1999). Briefly, the voltage was converted to a distance using the circumference of the wheel, the data was low pass filtered at 10 Hz, and velocity was obtained by finite differences. The tachometer data was ten times the sampling rate of the marker data in order to ensure a precise measure of instantaneous belt velocity. The voltage output from the tachometer was proportional to the circumference of the wheel and, therefore to the distance traveled along the belt. The reset zone of the potentiometer encompassed 7% of the signal and was replaced with constant velocity. Twelve stance and step phases were averaged for each trial and normalized to 100% stance and 100% step, respectively. The variation of the belt speed was expressed as the difference between the maximal and minimal belt velocity as a percentage of average velocity during stance.

Instantaneous horizontal velocity of the right heel, right metatarsal-phalangeal joint, and the right toe were obtained from the first-order finite difference of the position data in order to compare with the tachometer results and, subsequently, give an indication of the accuracy of the tachometer. Unloaded treadmill belt velocity was measured immediately following each trial and processed in the same way as the trials with the runner to allow direct comparison and to give an indication of the precision of the tachometer.

3.4.3 Horizontal Force

In order to obtain a measure of the horizontal reaction force between the runner and the treadmill belt (F_x) without having a force platform built into the treadmill, an inverse dynamics approach was used. This procedure was shown by Bobbert et al. (1991) to be fairly accurate in the vertical direction. The procedure used in this study was similar to that of Bobbert's except that rods were not used on the lower limb to maintain fixed segment lengths and all data were filtered at 10 Hz as opposed to filtering distal segment data at a higher frequency (50 Hz). Bilateral symmetry was assumed in order to create data for the left elbow and wrist. All joint co-ordinate data were then averaged across the twelve stance phases and were used along with the anthropometric data displayed in Table 2 (Winter, 1990) to calculate the horizontal position of the whole body center of mass (x_{CM}) at each instant, i, with respect to the lab using the following formula:

$$x_{CM_i} = \frac{\sum_{j=1}^{N} x_j * m_j}{\sum_{j=1}^{N} m_j} \tag{1}$$

where horizontal position of the center of mass of a given segment (N = 12) was represented by x_j and the mass of that segment was represented by m_j. The a_{CM} at each instant, i, was then computed by the second-order finite difference of x_{CM_i} as shown in formula 2:

$$a_{CM_i} = \frac{\left(x_{CM_{i+1}} - 2x_{CM_i} + x_{CM_{i-1}}\right)}{\Delta t^2} \tag{2}$$

where Δt is the time between adjacent samples. As can be seen from this formula, a_{CM} can not be determined for the first and last points of the stance phases and therefore, these points were assumed to be zero since no horizontal force would occur at these points. For certain overground trials of model validation, extra points were retained during data processing so that first and last points were not forced to be zero. If the calculated horizontal force

Table 2. Normative Anthropometric Values

Segment	Definition	Segment Mass / TBM	Centre of mass / Segment Length (Proximal)
Foot (x2)	Lateral malleolus / Head of metatarsal II	0.0145 M	0.50
Leg (x2)	Femoral condyles / Medial malleolus	0.0465 M	0.433
Thigh (x2)	Greater trochanter / Femoral condyles	0.100 M	0.433
Trunk Head Neck	Greater trochanter / Glenohumeral joint	0.678 M	0.66
Upper Arm (x2)	Glenohumeral axis / Elbow axis	0.028 M	0.436
Forearm and Hand (x2)	Elbow axis / Ulnar styloid	0.022 M	0.682

TBM = Total Body Mass

Source Code: M, Dempster via Miller and Nelson; *Biomechanics of Sport*, Lea and Febiger, Philadelphia, 1973 from Winter (1990); *Biomechanics and Motor Control of Human Movement*, John Wiley & Sons, New York.

deviates from zero at these instances, error in the methodology. The final step was to calculate the F_x applied by the treadmill belt that would cause these accelerations of the CM by using Newton's second law as shown below:

$$F_{x_i} = TBM * a_{CM_{x_i}} \tag{3}$$

where TBM is the total body mass of the subject. All F_x data were normalized to 100% of stance phase using cubic spline interpolation.

3.4.4 Model Validation

Various trials with various subjects running overground on the force platform were analyzed for comparison with the F_x as calculated from simultaneously recorded marker co-ordinate data. The measure of the fore-aft force (GRF_x) was obtained from the recorded data in millivolts using the AMTI calibration matrix.

3.4.5 Kinetic Energy

In order to put the amount of work being done by the treadmill on the runner into context, an estimate of the linear kinetic energy of the centre of mass of the body (E_{kin}) with respect to the belt was obtained. The instantaneous velocity of the centre of mass (v_{CM_i}) was determined by the first-order finite difference of the x_{CM_i} and then substituted into the following formula:

$$E_{kin_i} = 0.5 * m * (v_{CM_i} + v_{B_i})^2 \tag{4}$$

where m is the total body mass and v_{B_i} is the instant velocity of the belt. The resulting velocity term represented the velocity of the CM of the runner with respect to the belt. The amount of eccentric and concentric work performed was obtained from the negative and positive change in kinetic energy, respectively, during each phase (ΔE_{ecc} = total negative work and ΔE_{con} = total positive work).

3.4.6 Power

The power (P_x) that is transferred from the treadmill to the foot at each instant, i, was calculated using the following formula:

$$P_{x_i} = F_{x_i} * (v_{B_i} - v_{B_{RHC}}) \tag{5}$$

where F_{x_i} is the calculated force that the treadmill applied to the runner, v_{B_i} is the instant velocity of foot and belt, and $v_{B_{RHC}}$ is the initial velocity of the foot/belt system at right heel contact. The resulting velocity term will be an indication of the amount of fluctuation that the force is causing. If equation 5 was applied to overground running, the instant velocity of the ground always equals the velocity at initial contact and, therefore the resulting velocity term is zero and no power is transferred. Refer to Figure 3 for a schematic representation of the expected powers for overground and treadmill running.

3.5.7 Work

The work done by the treadmill (W_x) was calculated from the integral of P_x with respect to time, as shown in equation (6) below:

$$W_{x_i} = \int_{i=1}^{t} P_{x_i} * dt \tag{6}$$

where dt is the change in time that has been adjusted according to the effective increase in sampling rate that occurred as a result of interpolation to 101 data points and t is the stance time. The stance phase was subdivided into eccentric and concentric portions as indicated by the negative and positive phases of F_x. The amount of work done in each of the eccentric (W_{ecc}) and concentric (W_{con}) phases were determined from the difference in work across the phase. The work done (W_{ecc} and W_{con}) was then expressed as a percent of the corresponding ΔE_{kin}, as shown for W_{ecc} below:

$$\%W_{ecc} = \left(\frac{W_{ecc}}{\Delta E_{ecc}}\right) * 100\% \tag{7}$$

3.4.8 Statistical Measures

Multiple linear regression analysis was used to quantify the effect of TBM and

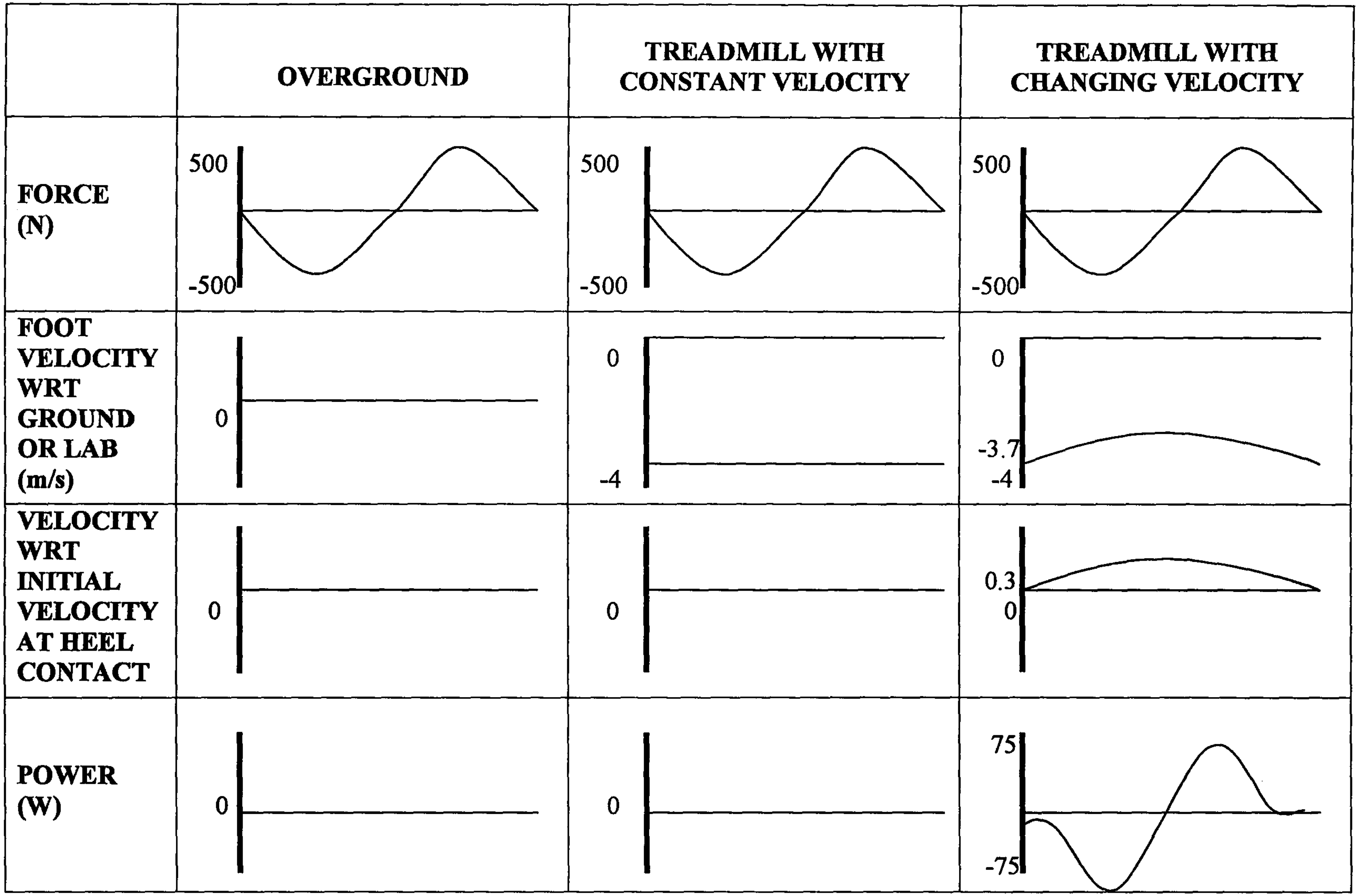

Figure 3. Flow Chart of Expected Power Transfers in Different Situations using the Proposed Method of Calculation

treadmill speed setting on intra-step belt-speed variation expressed as a percent of average belt velocity during stance. An identical analysis was performed on the ΔE_{ecc}, ΔE_{con}, $\%W_{ecc}$ and $\%W_{con}$. Regression equations and coefficients of determination (r^2) are presented to describe the effects of the independent variables on the calculated measures.

Chapter 4

Results

4.1 Event Identification

As mentioned in the methods section, the ensemble process was simplified by choosing the average number of frames rather than interpolating to obtain an equal number of data points between identified RHC and RTO or LHC events. The number of frames in the stance or step phase for a given trial typically had a maximum variation of only plus or minus one frame. Therefore, with RHC events lined up, the actual RTO or LHC event at the end of the file was still determined within approximately +/- 3 %. The GRF_x from force plate measurements identified the RHC and RTO events as being within one frame of the corresponding event as determined from marker acceleration data.

When expressed as a percent of the entire step, the time spent in stance was dependent on the mass of the runner and the speed of running. The results showed an increase in percent stance from an average (+/-sd) of 68 (3.3) % for the 55.2 kg subject to 80 (4.2) % for the 99.6 kg subject. A linear decrease in percent stance from an average of 82 (6.0) % at 2.7 m/s to 71 (4.8) % at 4.0 m/s was also found. Refer to Appendix A for complete tables of kinematic data.

4.2 Treadmill Belt Velocity

The results of treadmill belt velocity show the tachometer to be quite reliable. An ensemble and standard deviation for the 99.6 kg subject at 4.0 m/s including simultaneous measures of foot marker velocities is shown in Figure 4. It can be seen that the step-to-step variation is very small. Figure 5 shows a comparison of the treadmill belt velocities for the unloaded treadmill and for an average step of the 77.7 kg subject at all four speed settings (2.7, 3.1, 3.6 and 4.0 m/s). Figure 6 displays the treadmill velocities for an average step at 4.0 m/s for all five subjects (55.2, 66.7, 77.7, 89.3 and 99.6 kg). Refer to Appendix A for similar graphs at 2.7, 3.1 and 3.6 m/s. Figure 6 demonstrates the precision of the tachometer as well. The average standard deviation for all five baseline trials shown was 0.012 m/s. At the speeds studied, the actual belt velocity without a runner as measured by tachometer was an average (+/-sd) of 0.90 (0.12) % higher than the speed setting indicated. With a runner, the average belt velocity over the entire 10 seconds of collection was 0.66 (0.27) % higher while the average during the right step was 0.60 (0.30) % higher. This indicates that the average inter-subject right step velocity was about 0.12 % slower than the left. The belt velocity during the right stance phase alone was only 0.31 (0.37) % higher than the speed setting indicated.

For the purpose of determining the ability of average belt velocity to predict the equivalent overground velocity, the change in belt velocity while the runner was not in contact with it was analyzed. The average increase in belt velocity during the short flight phase (13.5 % of step) was 0.64 (0.25) %. This increase occurred in a relatively linear fashion leading to an average of 0.32 % overestimation for 13.5 % of step, thus increasing the average step value by 0.043%. Therefore, the actual running velocity that compares to overground is 0.62 % (0.66 - 0.043) higher than the displayed speed setting,

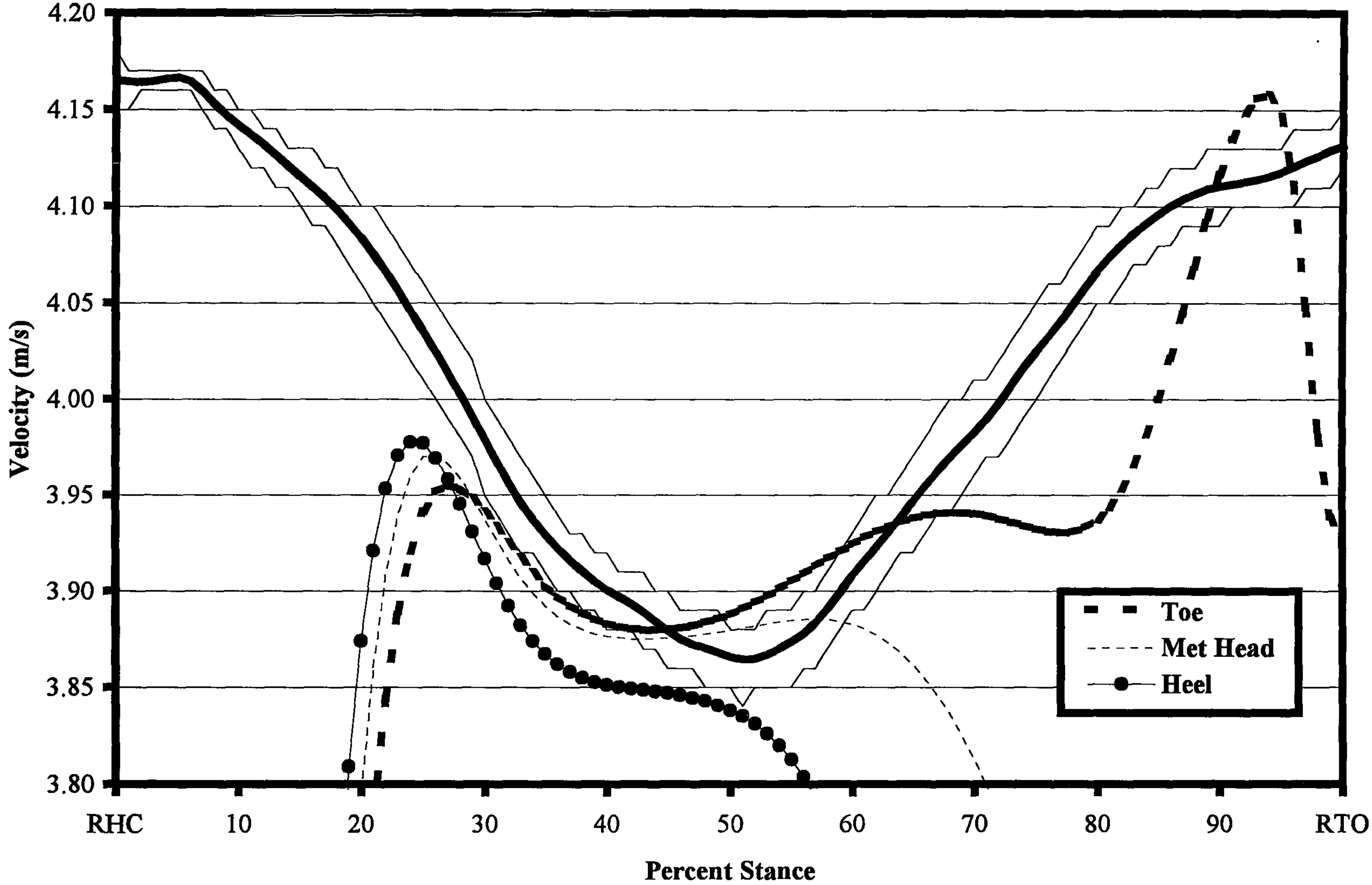

Figure 4. Ensemble Average of Belt Velocity +/- sd and Foot Marker Velocity for the 99.6 kg Subject at 4.0 m/s

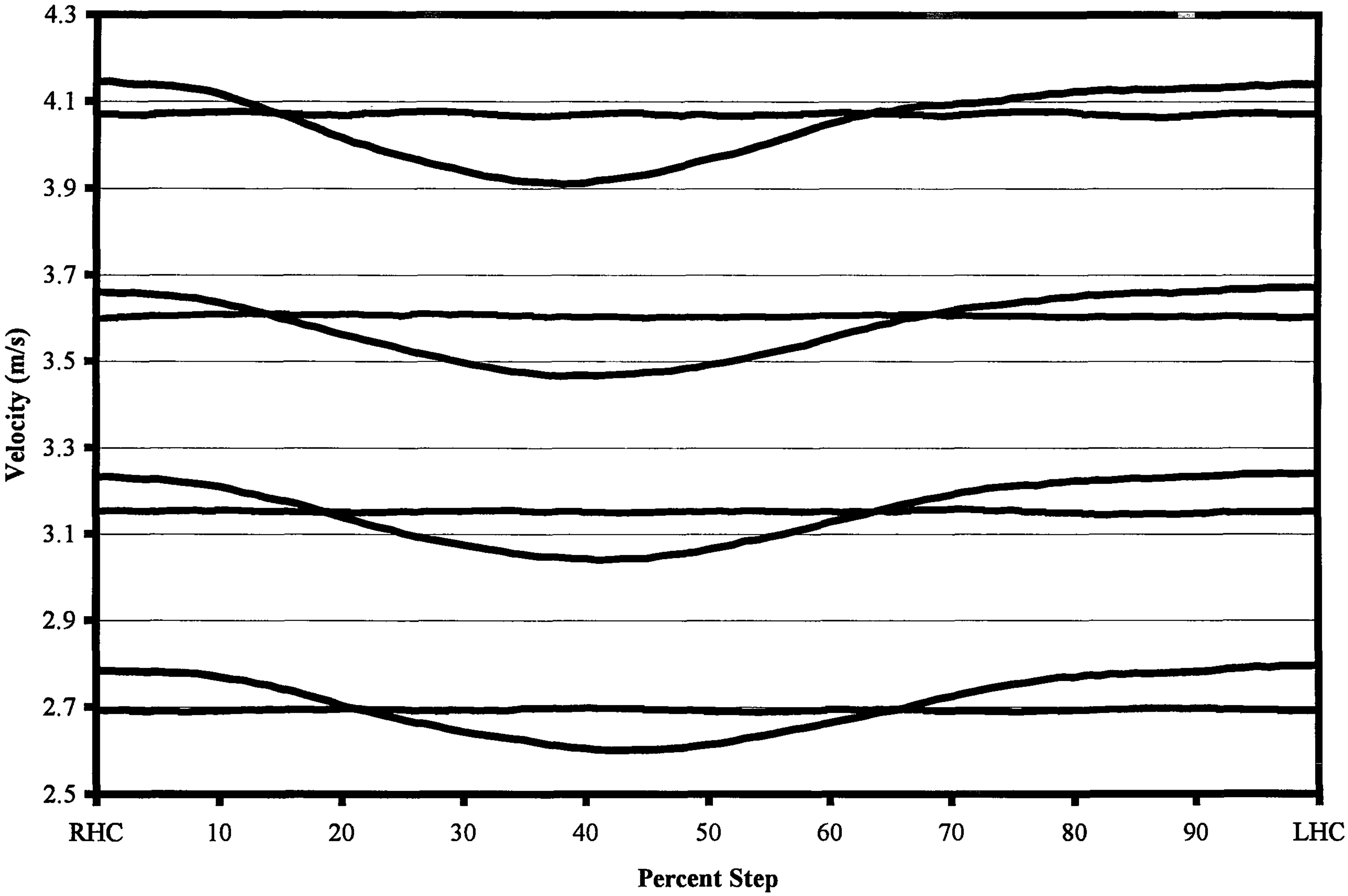

Figure 5. Instantaneous Treadmill Belt Velocity at all Speed Settings With and Without a 77.7 kg Subject

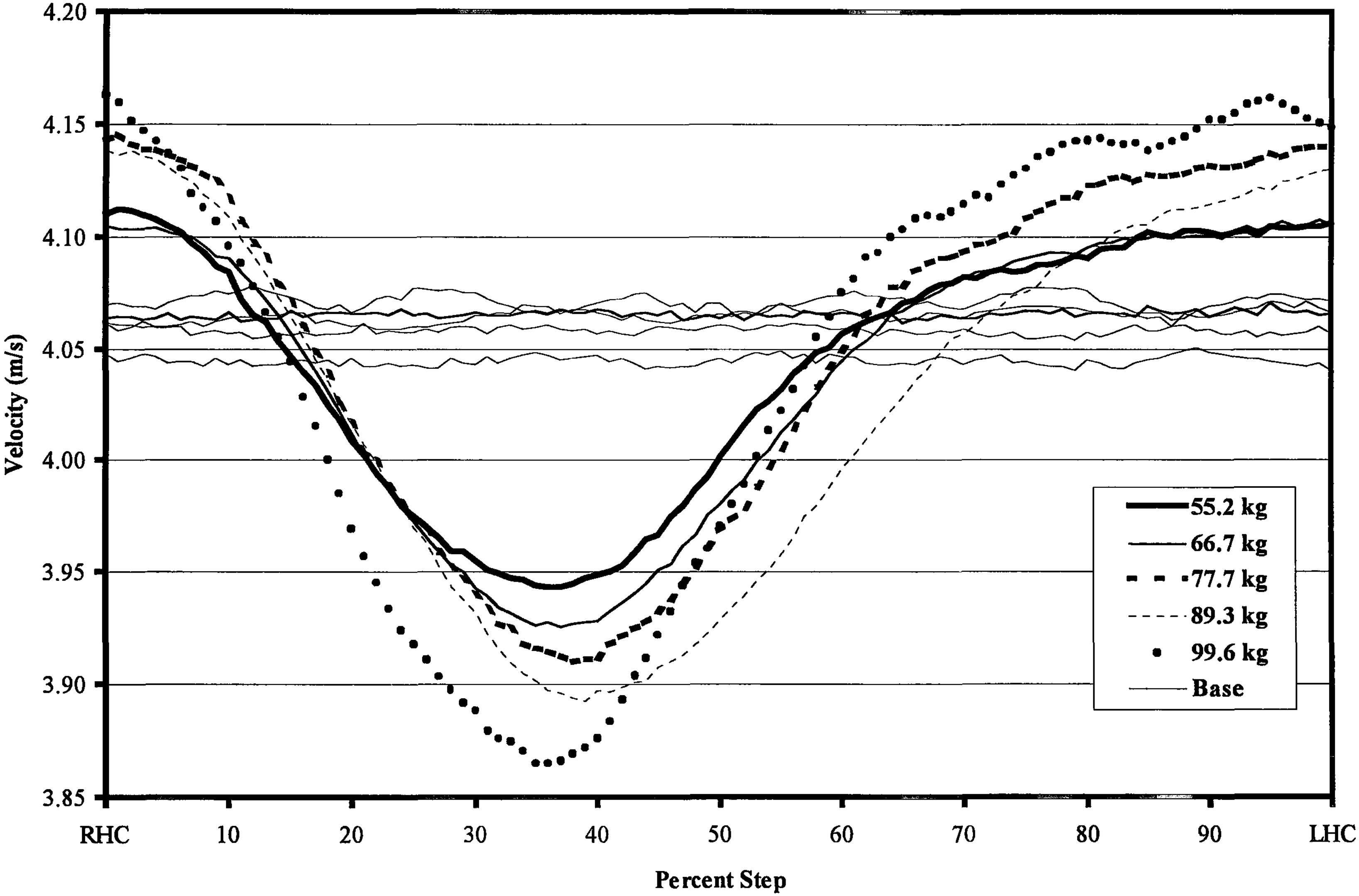

Figure 6. Instantaneous Treadmill Belt Velocity of all Subjects and all Baselines at the 4.0 m/s Setting

or 0.20 % (0.90 – 0.66 + 0.043) lower than the unloaded belt velocity.

The effect of TBM and treadmill speed setting on the percent variation of the treadmill velocity during a step is presented in Table 3.

Table 3. Factors Affecting Intra-Step Belt Velocity Variation

Factor	Coefficient	P – value	Partial R^2
Subject's mass	0.0788 %/kg	0.0000	0.858
Speed setting	-0.840 %/m/s	0.181	0.097
Intercept	2.758 %		
Total R^2 =0.955			

The coefficient gives the absolute effect of the factor on the variation, the P–value denotes the significance, the partial R^2 indicates the amount of variation that is accounted for by the factor and the total R^2 indicates the amount of variation explained by the model

The subject's mass and the speed setting predicted 95.5% of the variation ($\alpha > 0.01$) in the output measure for the treadmill used as given by the following formula:

$$\%\text{VAR} = 0.0788 * \text{TBM} - 0.840 * \text{SPEED} + 2.758 \tag{8}$$

where %VAR is the variation in belt velocity with respect to average belt velocity, TBM is the total body mass (kg) and SPEED is the treadmill setting (m/s). The percent variation of the treadmill belt velocity for all trials are displayed graphically in Figure 7. Since TBM had the greatest affect on %VAR, it was placed on the horizontal axis of this line graph as well as others to show it's affect.

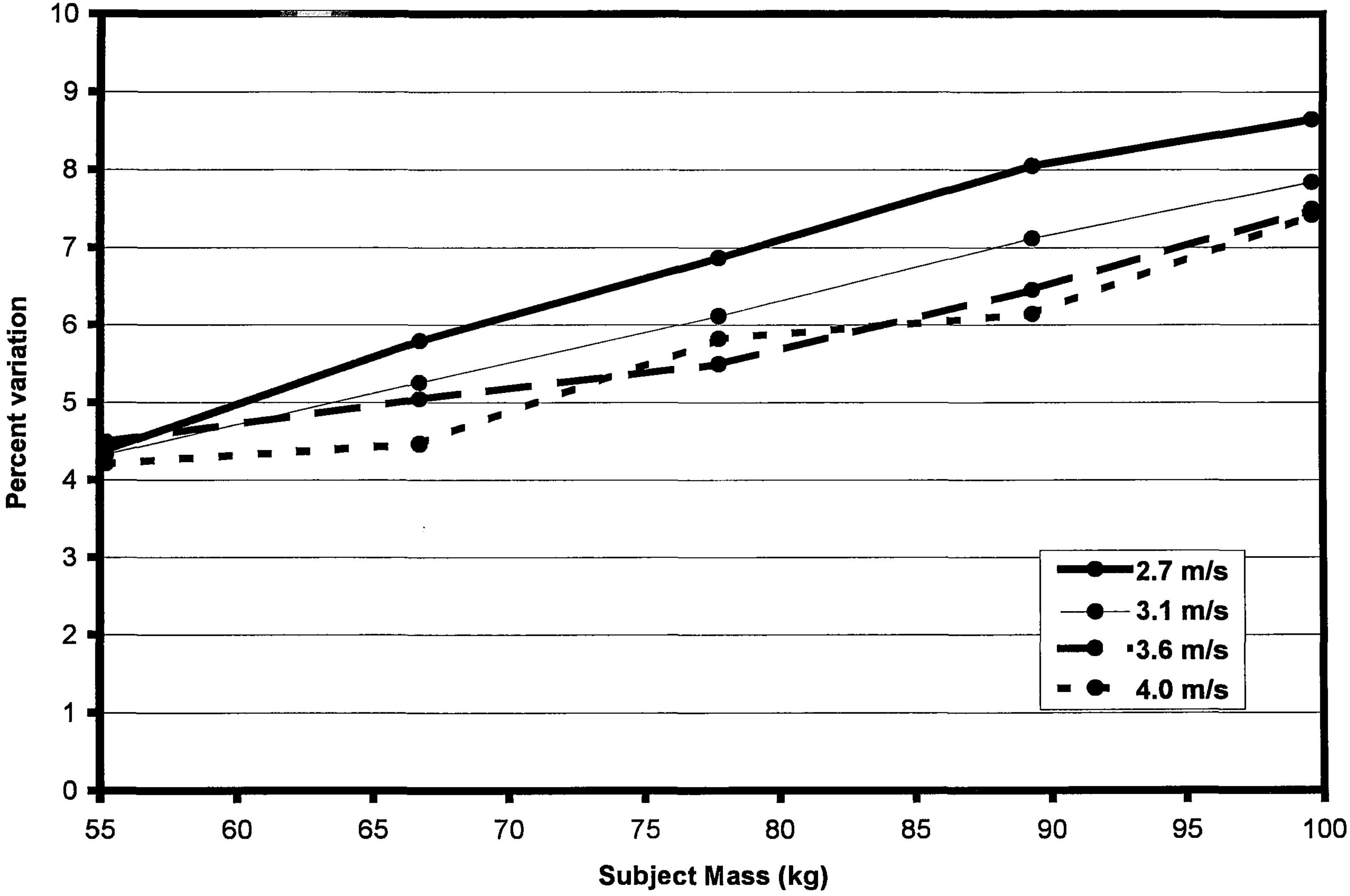

Figure 7. Percent Variation of Treadmill Belt Velocity for all Five Subjects at all Four Treadmill Settings

4.3 Model Validation

Examples of the comparison between the simultaneous calculation of the horizontal reaction force using marker accelerations (F_x) and the force platform measurement are shown in Figures 8 and 9. Figure 8 includes additional signals calculated using cutoff frequencies of 30 Hz and 6 Hz for all markers. Figure 9 includes an additional signal calculated using the cutoff frequencies from Bobbert et al. (1991) (legs and arms at 50 Hz, hip at 20 Hz and trunk at 15 Hz). Figure 9 also illustrates the error that occurs in the calculated force if the first and last data points are not set at zero. The force platform trace does not cross zero at RHC and RTO as a result of endpoint error during filtering at 10 Hz. Additional experimentation with lower cutoff frequencies eventually resulted in a two phase signal (4 Hz), however, the magnitudes were severely reduced. The cutoff frequency of 10 Hz appears to be the best choice and was, therefore, used in this study. Although the calculated F_x does not appear to be a good predictor of the GRF_x as measured by the force platform, the prediction is best during the middle third of stance. It will be shown later that this region contains the important power transfer between the belt and the foot.

Furthermore, it is noted that these overground measurements only allow an ensemble of one while the treadmill trials permit an ensemble of twelve trails. The greater number of trials in the treadmill ensemble allowed greater noise reduction and likely a better estimate than in the overground trial. It is, however, acknowledged that further calculations using the F_x will be considered as estimations. An example of the contribution of each segment to the calculated F_x is illustrated in Figure 10. Only

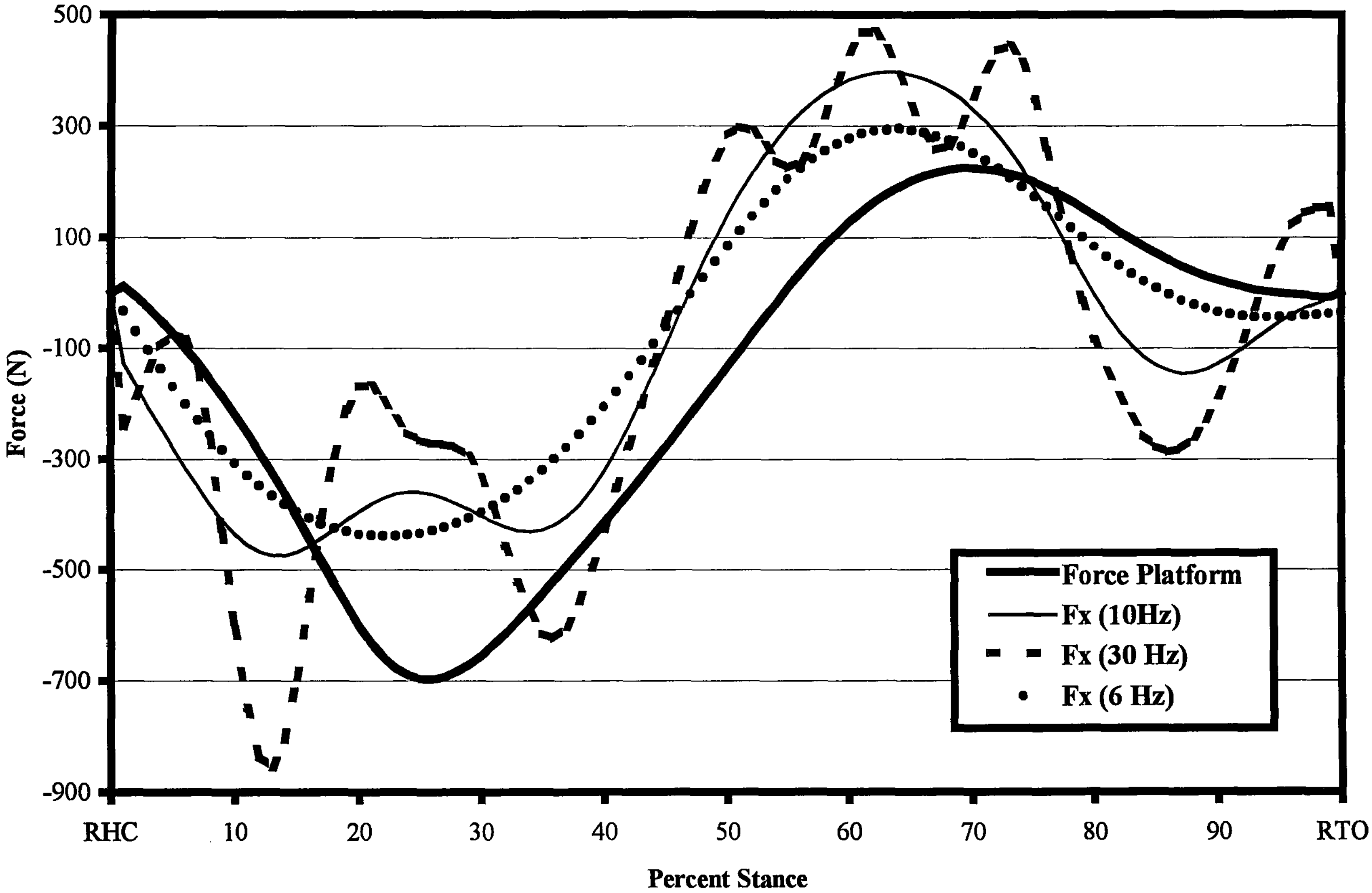

Figure 8. Comparison of Calculated and Measured Horizontal Reaction Force of the 55.2 kg Subject Running 4.11 m/s

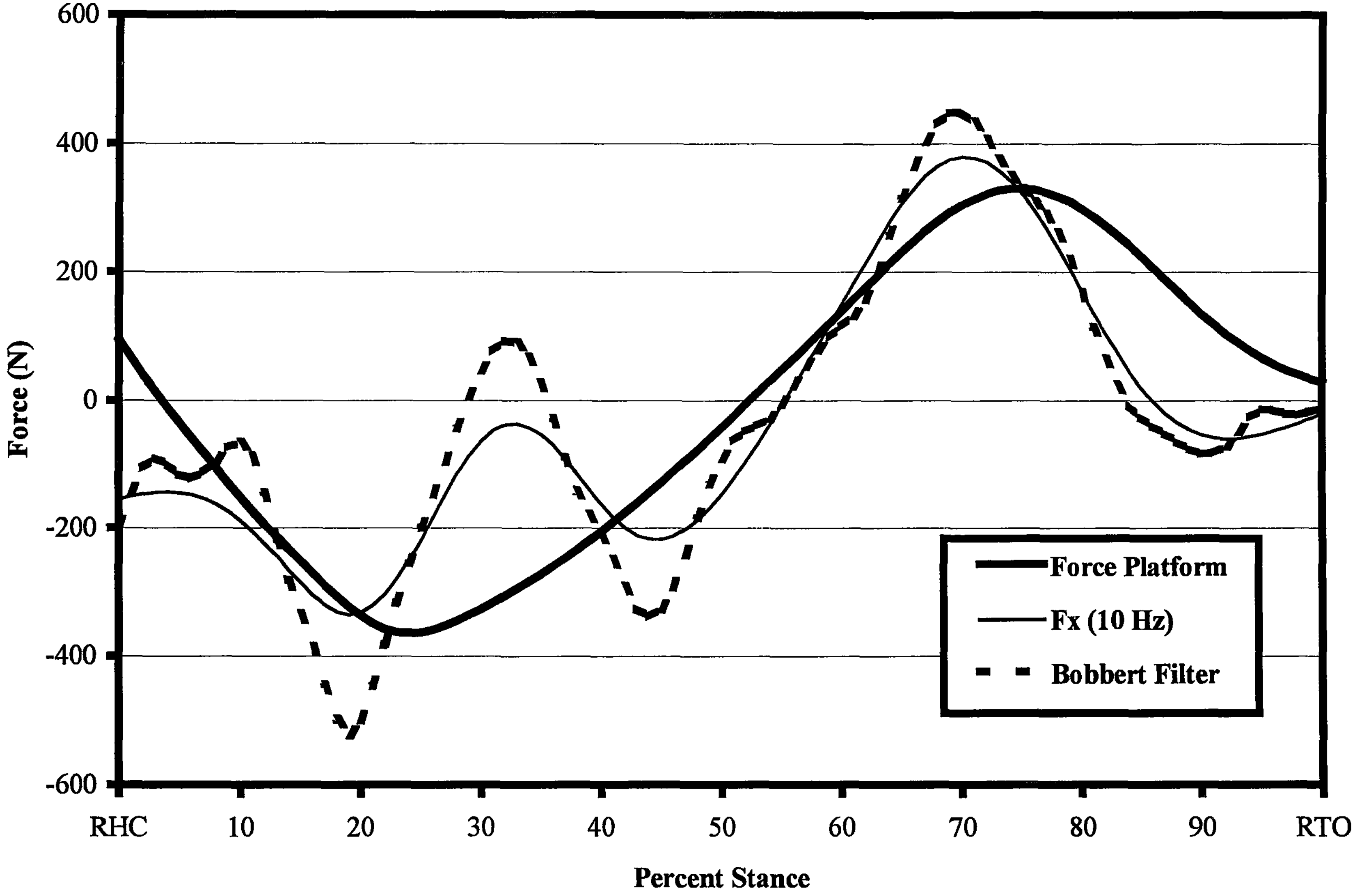

Figure 9. Comparison of Calculated and Measured Horizontal Reaction Force for the 77.7 kg Subject Running 2.87 m/s

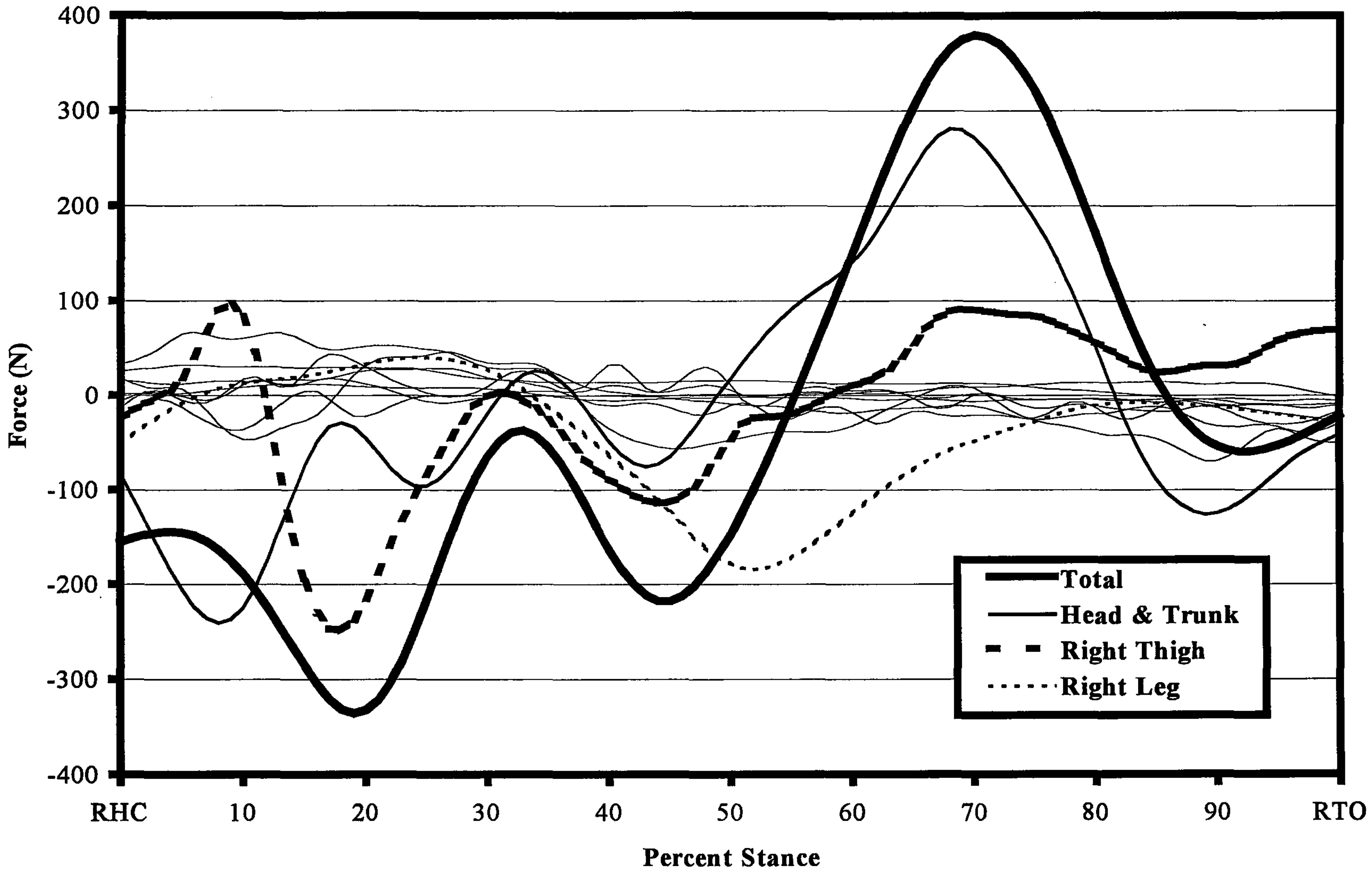

Figure 10. Segmental Contributions to the Horizontal Reaction Force on the CM for the 77.7 kg Subject Running 2.87 m/s (only segments that make a major contribution to the force on the whole body appear in the legend)

segments that make a noticeable contribution to the overall force appear in the legend.

4.4 Horizontal Force

The calculated horizontal reaction forces at each speed for the 77.7 kg subject are shown in Figure 11. As an example of the inter-stance consistency in the ensemble, the average standard deviation for the 4.0 m/s trial was +/- 26.9 N. Refer to Appendix B for similar graphical illustrations of F_x for the remaining subjects. Figure 12 shows a comparison of F_x for all subjects at the 4.0 m/s setting. A comparison of Figure 11 and 12 shows that intra-subject variation is relatively small while inter-subject variation is relatively large, suggesting some predictive power of the F_x calculation. In order of speed from slowest to fastest, the durations of the negative phase as a percent of stance were 53.6, 55.4, 57.2, and 59.0 %. Analysis of the eccentric impulse compared to the concentric impulse (areas under the force curve) revealed that the average impulse (+/-sd) of the entire stride was -4.50 (2.67) N·s. Expressed as a percent of the average negative impulse, a value of 13.4 % is obtained. This must be attributed to error in the calculated force signal since equal positive and negative impulses are required to maintain constant speed in order to stay on the treadmill.

4.5 Kinetic Energy

The results of the change in linear kinetic energy for eccentric (ΔE_{ecc}) and concentric (ΔE_{con}) phases of stance are displayed in Figures 13 and 14. The average (+/-sd) for ΔE_{ecc} across all trials was –40.6 (23.6) J and for ΔE_{con} was 36.0 (20.4) J. Since

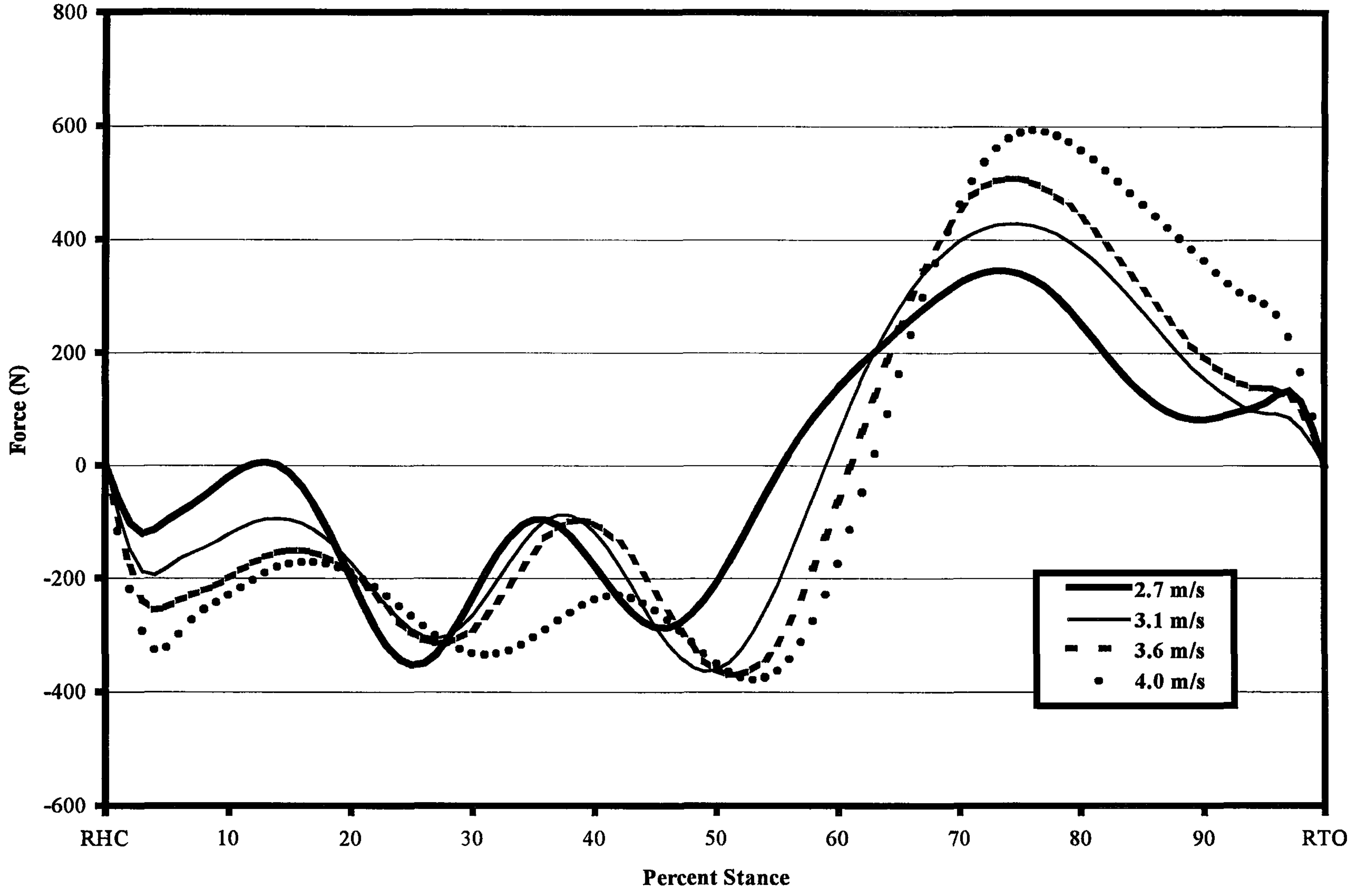

Figure 11. Horizontal Reaction Forces at all Treadmill Speeds for the 77.7 kg Subject

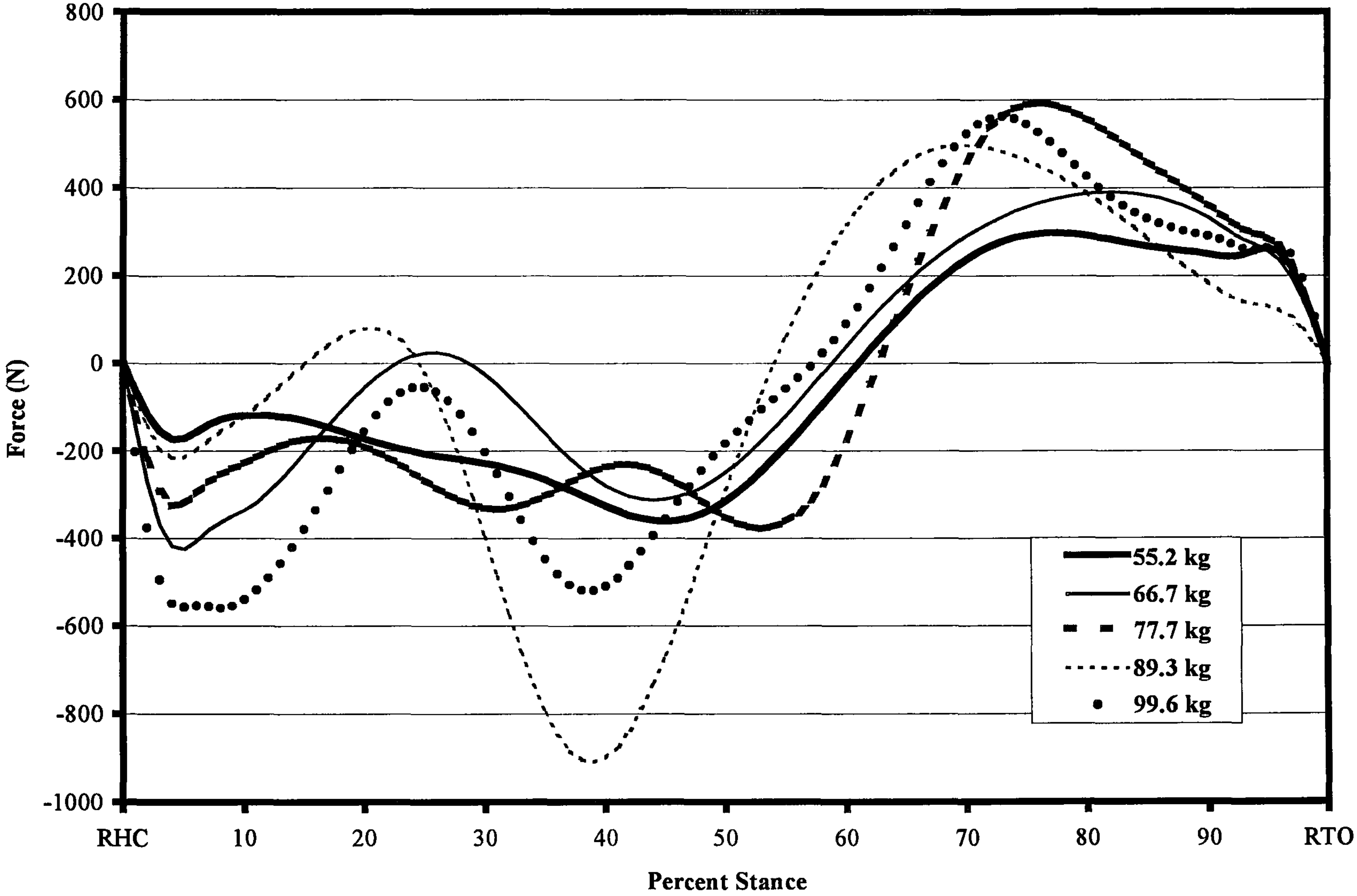

Figure 12. Comparison of Horizontal Reaction Forces for all Subjects at the 4.0 m/s Setting

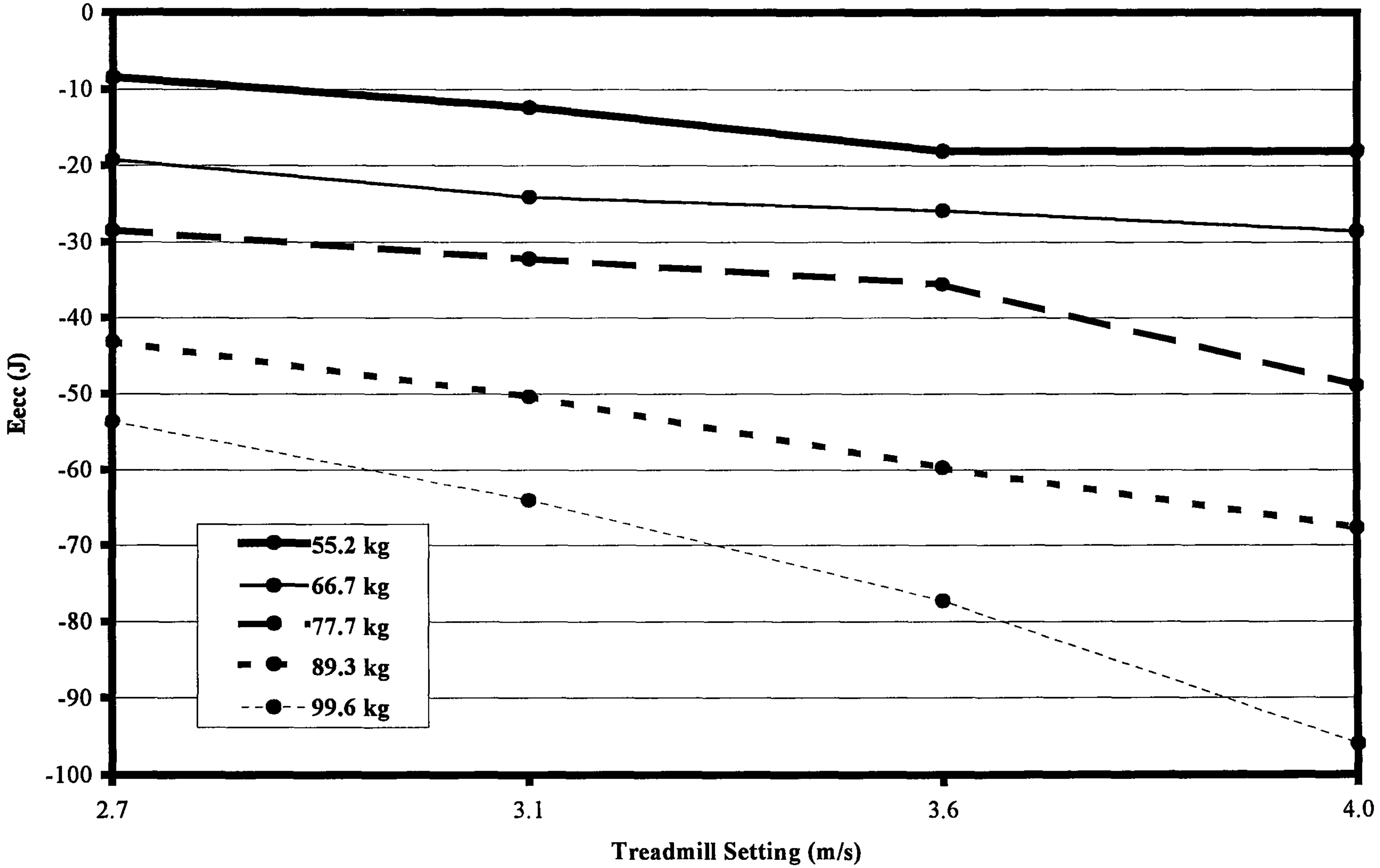

Figure 13. Change in Horizontal Kinetic Energy of each Runner during the Eccentric Phase (ΔE_{ecc}) for all Speeds

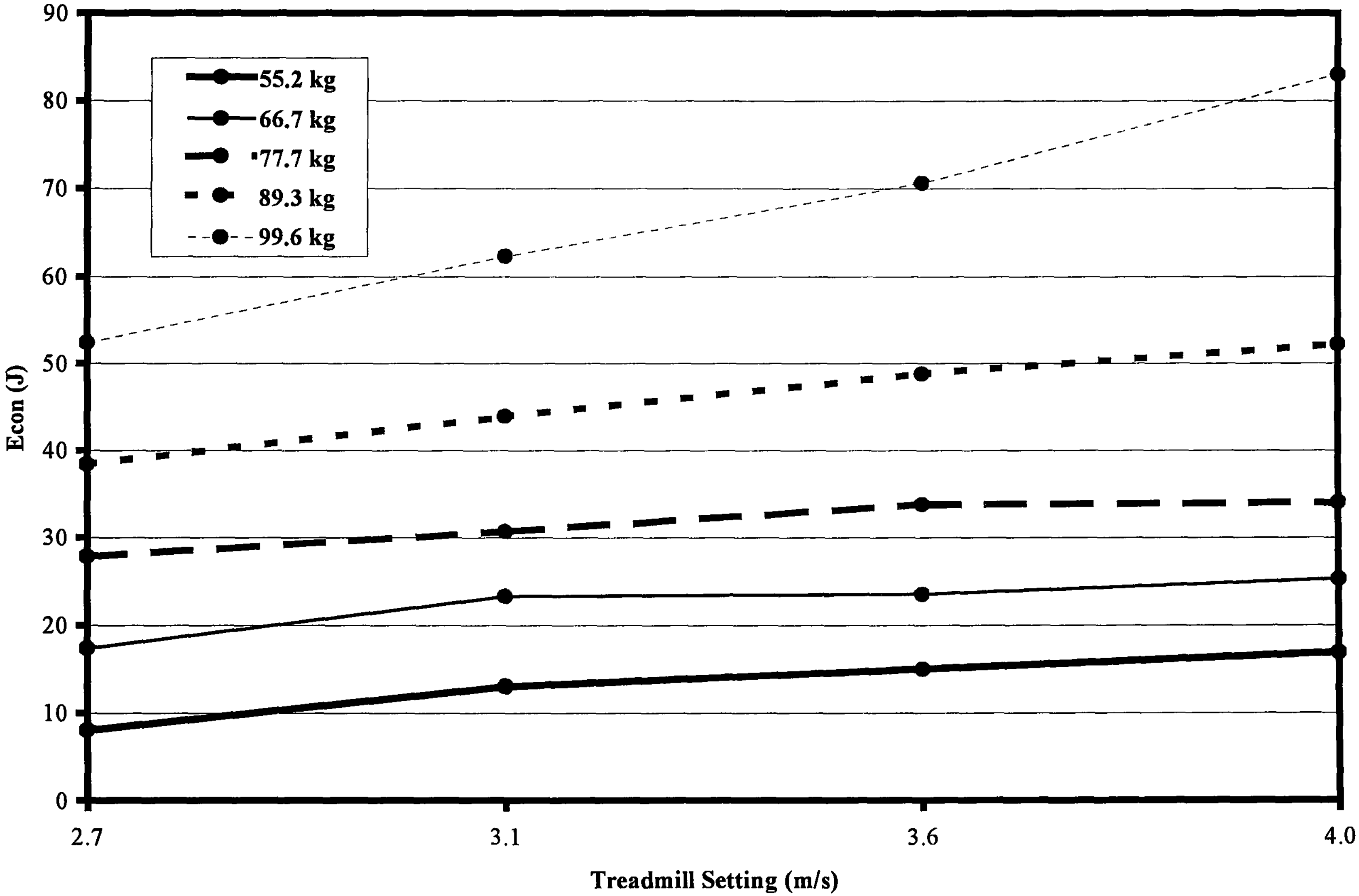

Figure 14. Change in Horizontal Kinetic Energy of each Runner during the Concentric Phase (ΔE_{con}) for all Speeds

and positive work is required to remain at constant speed and on the treadmill, it was expected that the average discrepancy of –4.6 J each stance phase was a function of the increase in treadmill belt speed during the flight phase. As confirmation of this assumption, the belt speed increased, on average, from 3.43 m/s to 3.452 m/s which translated to 5.9 J of kinetic energy. Multiple regression analyses revealed the following prediction equations for ΔE_{ecc} and ΔE_{con}:

$$\Delta E_{ecc} = -1.3229 * TBM - 15.7559 * SPEED + 114.9757 \quad (9)$$

$$\Delta E_{con} = 1.1743 * TBM + 9.8826 * SPEED - 88.3634 \quad (10)$$

TBM and SPEED accounted for 94.1 % of the variance in ΔE_{ecc} and 93.2 % of the variance in ΔE_{con}. All correlations were significant at greater than $\alpha = 0.01$. Regression summary tables are found in Appendix D.

4.6 Power

Graphical illustration of the treadmill power calculations for the 77.7 kg subject are shown in Figure 15. The initial phase of negative power is described as energy flow from the foot to the treadmill while the subsequent phase of positive power is described as energy flow from the treadmill to the foot. Refer to Appendix C for graphs of the other subjects.

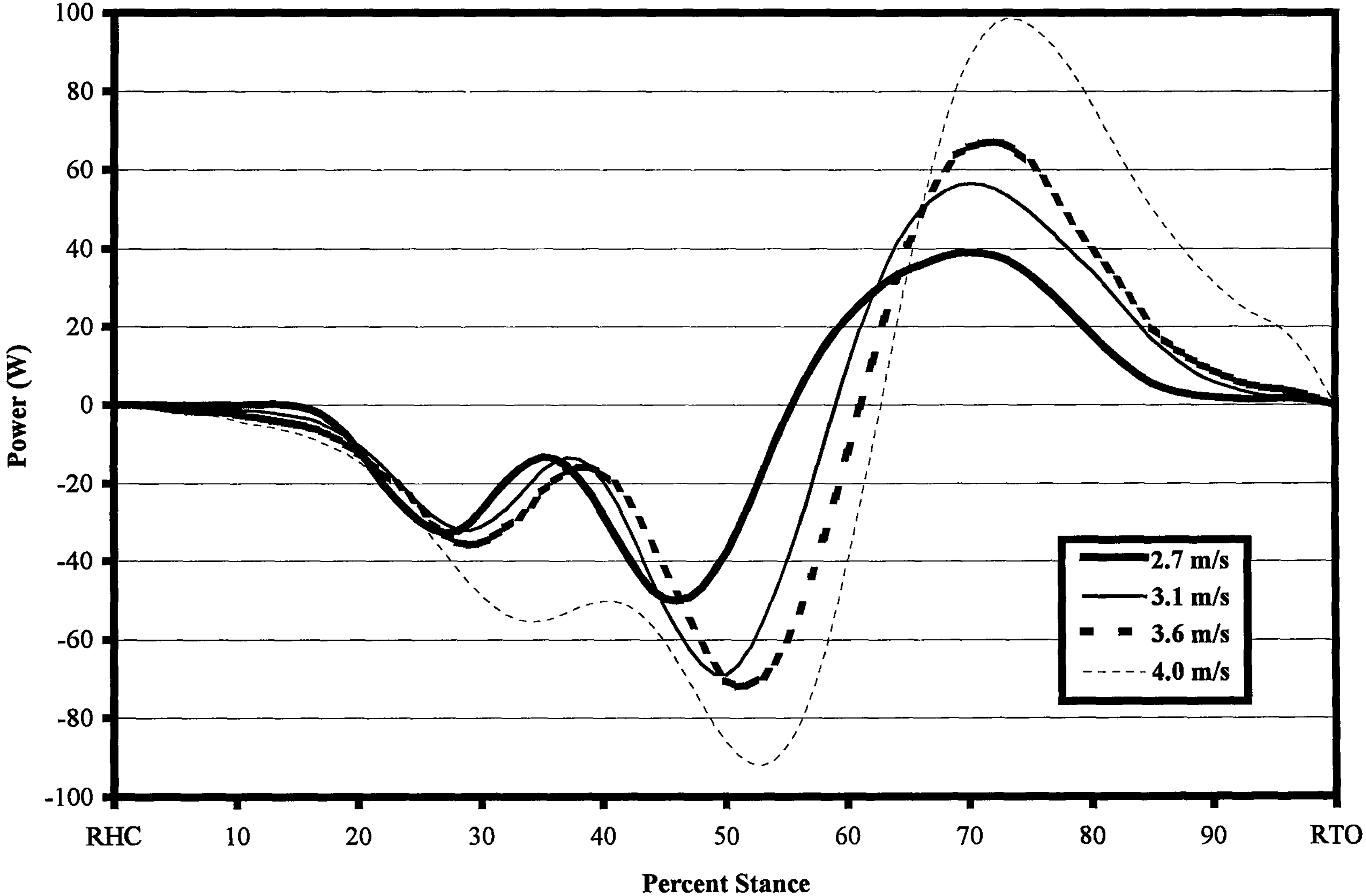

Figure 15. Treadmill Power Calculations for the 77.7 kg Subject at all Speeds

4.7 Work

Work was calculated from the area under the power curve. The region of negative power that occurred during the eccentric phase of running represented work being done on the treadmill (W_{ecc}). The region of positive power that occurred during the concentric phase of running represented work being done on the runner (W_{con}). W_{ecc} and W_{con} are shown in Figures 16 and 17, respectively. The average (+/-sd) work done on the treadmill during the eccentric phase was 4.49 (1.58) J and on the runner during the concentric phase was 3.37 (1.32). Although the value during the eccentric phase is slightly larger than the work during the

concentric phase, the cost savings is more likely to be significant in the concentric phase since concentric work is more costly to the runner. Linear regression analysis revealed that the independent variables (TBM and SPEED) accounted for just 53.8 % of the variance in W_{ecc} and 54.8 % of the variance in W_{con} (see Appendix D for regression tables).

In order to qualify the amount of external work done by the treadmill, the values are also expressed as a relative percentage of the total change in horizontal kinetic energy of the CM with respect to the treadmill belt (ΔE_{kin}). The average (+/-sd) of all trials for $\%W_{ecc}$ and $\%W_{con}$ was 11.84 (5.59) % and 10.15 (5.13) %, respectively. Figures 18 and 19 show data from all trials for $\%W_{ecc}$ and $\%W_{con}$. It was evident that some inter-subject variable other than mass affected these measures. As expected, the results of the multiple regression analysis showed that 54.6 % of the variance in $\%W_{ecc}$ and 49.2 % of the variance in $\%W_{con}$ was explained by the subject's mass while the correlation to the

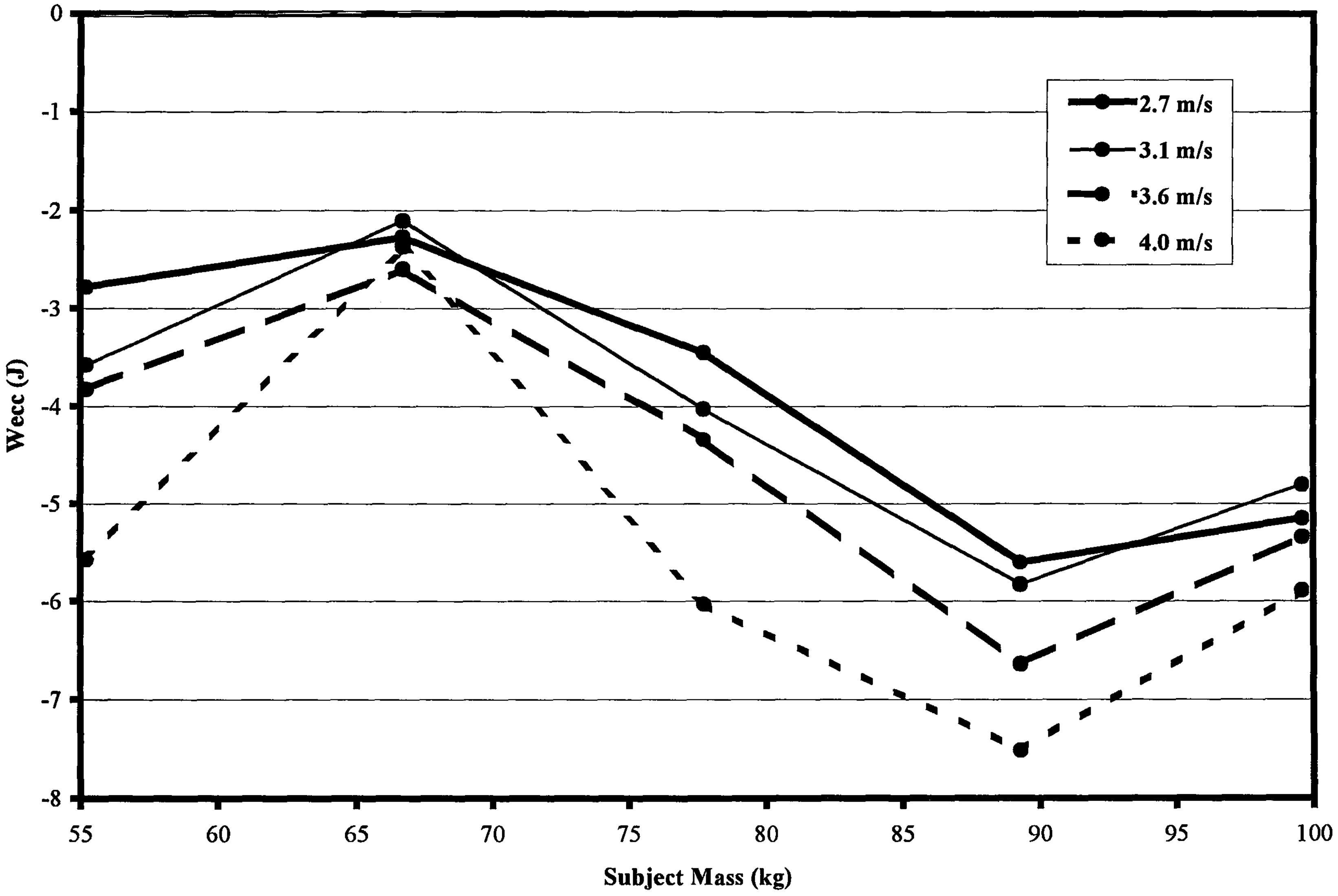

Figure 16. Work done by the Treadmill on the Runner during the Eccentric Phase of Stance

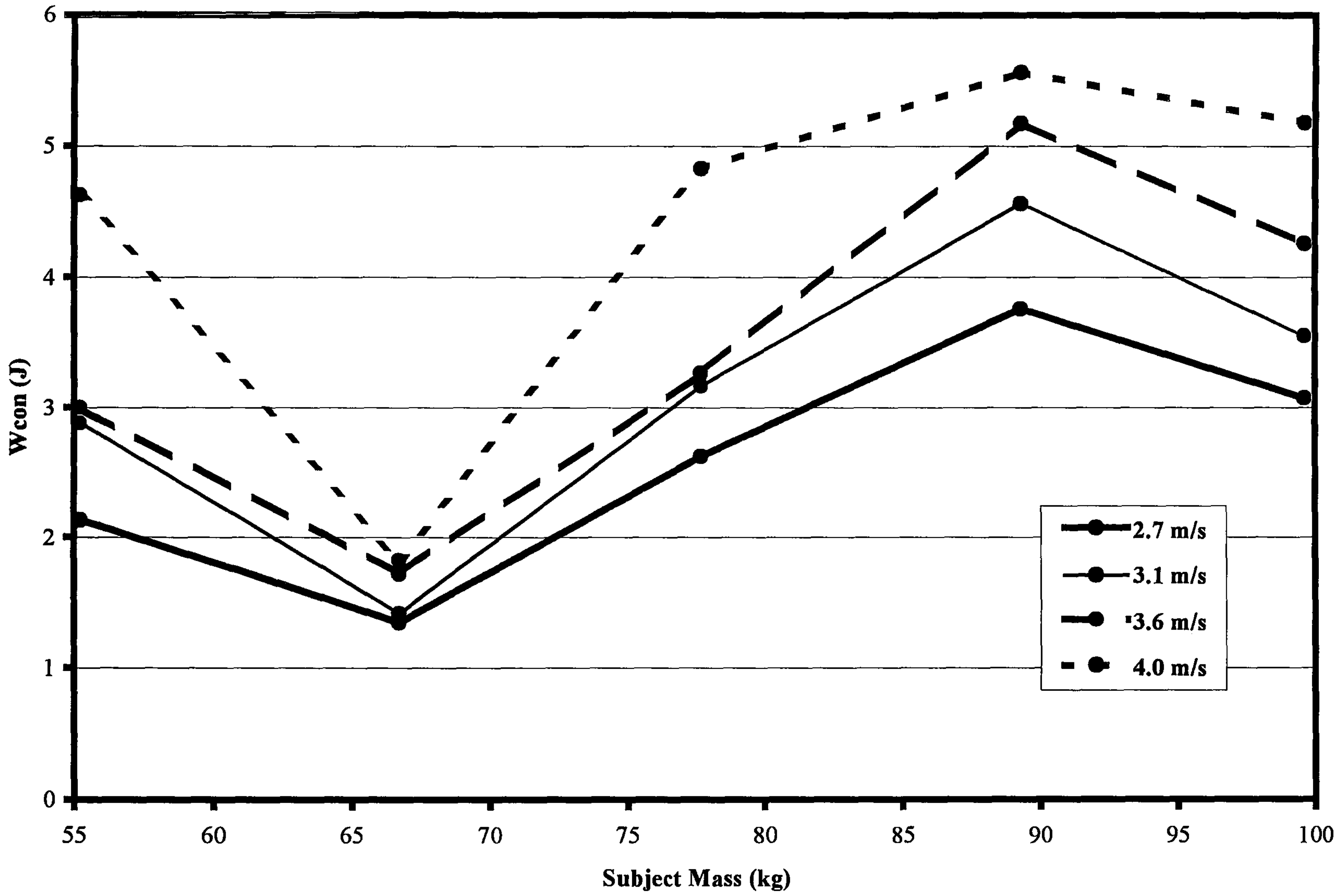

Figure 17. Work done by the Treadmill on the Runner during the Concentric Phase of Stance

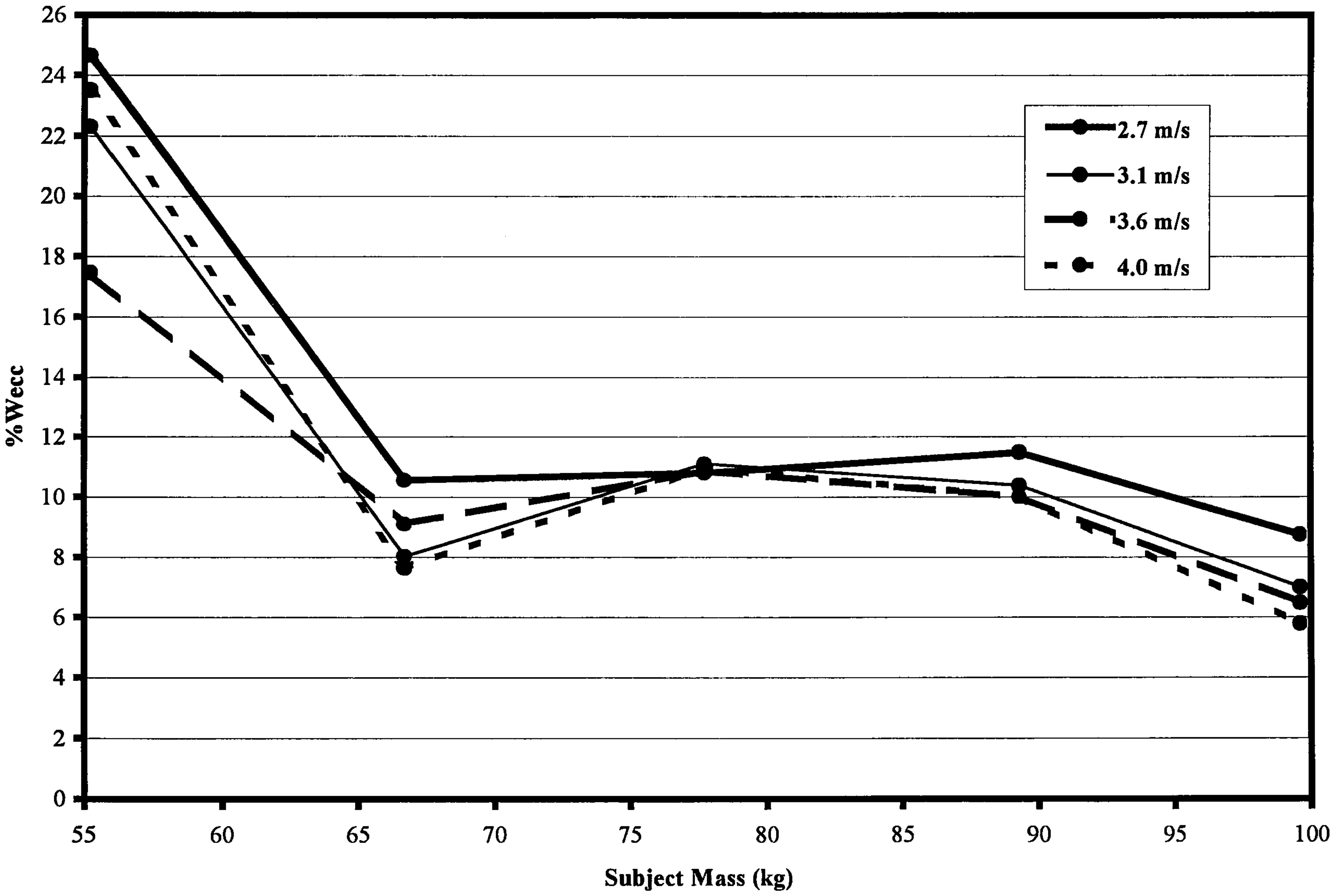

Figure 18. Percent Work done by the Treadmill during the Eccentric Phase of Stance for all Trials

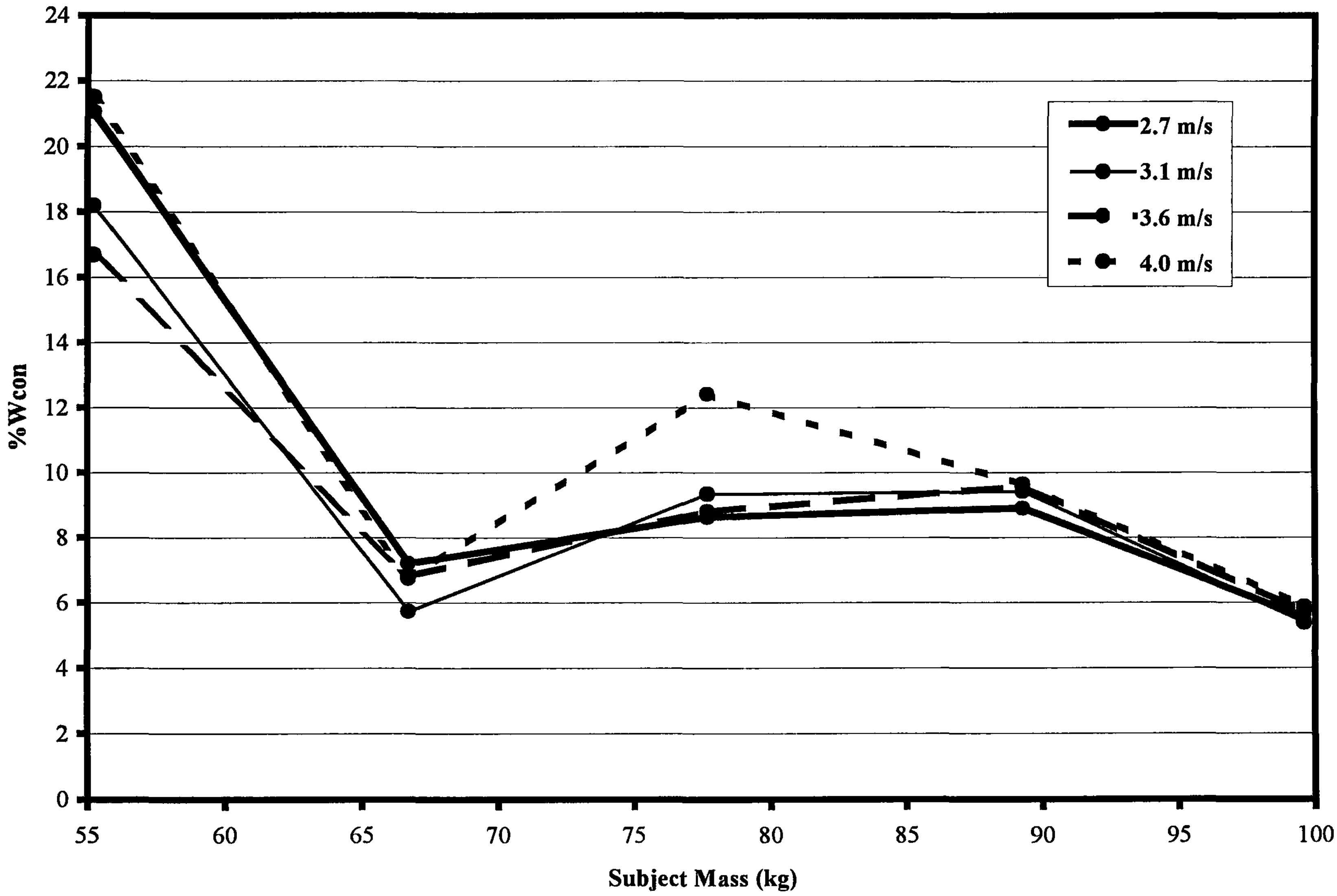

Figure 19. Percent Work done by the Treadmill during the Concentric Phase of Stance for all Trials

treadmill speed setting was negligible. From observation of the subjects, it was thought that running style may have had an affect on the treadmill's contribution to the work of running. Percent stance (%STANCE) was added to the linear regression equations to see if the predictions could be improved. The coefficient of determination did not improve significantly for $\%W_{ecc}$, but did improve to 61.7 % for $\%W_{con}$, as shown below:

$$\%W_{ecc} = -0.2555 * TBM + 31.6935 \tag{11}$$

$$\%W_{con} = -0.1425 * TBM - 0.3535 * \%STANCE + 48.2669 \tag{12}$$

Refer to Appendix D for the regression tables.

Chapter 5

Discussion

The main theme of the discussion is the numerical and theoretical validity of the calculated measures. Not only does the procedure need to be sensitive enough to produce an accurate measure, but this measure must also be a true measure that describes an actual difference between treadmill and overground running. The aim was to obtain a calculation procedure that would yield zero values for overground data, which is not a trivial matter when frame of reference issues arise.

5.1 Event Identification

Proper identification of the right heel contact, right toe off and left heel contact events was needed in order to determine the average stance or step phase. As indicated in the overground trials, the accuracy of event identification was within 3 % of the stance phase and, therefore, adequate enough to prevent loss of signal accuracy as a result of the ensemble process. Indeed, the small standard deviations of the ensembled data suggest that the repeated samples are in phase with one another.

It is acknowledged that some unilateral and bilateral inter-step variation will inevitably be lost in the ensemble of the right stance and the following swing phase. However, the purpose of this study was to quantify the overall effects of the interaction of runner with the treadmill, so limitation of the analysis to an ensemble average of the right side is an acceptable simplification.

5.2 Treadmill Belt Velocity

The accuracy of the tachometer for calculating instantaneous treadmill belt velocity had been shown to be very good in a previous independent study. Since the resolution of the OptoTrak data acquisition system is approximately one tenth of a millimeter, the likeness of the simultaneously recorded foot marker velocities in Figure 3 made a convincing case in this matter. In fact, the 1200 Hz sampling rate used in this study was far in excess of that required to identify the maximal and minimal speeds used in the quantification of intra-stride belt speed variation. The velocity signal is relatively sinusoidal with frequency of 1 Hz per step which translates to a range of 2.6 to 2.8 Hz at 2.7 and 4.0 m/s, respectively. The reason for the very high sampling rate was to ensure that no extra error would be introduced into the treadmill power calculation, even at high treadmill speeds. Indeed, any error introduced by the instantaneous belt velocity was negligible in comparison to the errors of the estimate of Fx.

One useful application of the tachometer data is to evaluate the calibration of the actual belt speed to the displayed speed setting for this specific treadmill. Since the unloaded belt velocity was on average 0.90 % higher than the display, the calibration was fairly accurate. Perhaps the manufacturers of the treadmill expected the belt to slow down when the load of a runner is added and tried to compensate for this effect. As predicted, the additional load of a runner reduced the relative offset to 0.66 % over the entire time of collection and 0.31 % during the stance period alone.

An interesting situation occurs when the average belt velocity is used to predict the equivalent overground velocity. It would seem appropriate to calculate the average velocity of the belt over an extended period of time since any error from the runner adjusting their position forward or backward on the treadmill during a particular stride would be nullified. In other words, since the runner's average velocity with respect to the lab must be zero, the average negative velocity of the belt with respect to the lab is equal to the positive velocity of the runner with respect to the belt. There is, however, one potential source of error that is introduced into this measure. This error occurs when any further increase in belt velocity during the flight phase is calculated into the average. It is physically impossible for the runner to increase their horizontal velocity since they are a projectile with no horizontal forces acting on them during this flight phase. As a result, average belt velocity as measured by a tachometer slightly overestimates the equivalent overground velocity. True running velocity should, therefore, be calculated using the instantaneous belt velocity during stance and a constant take off velocity during flight.

Given that the speed is generally already reduced to a greater extent as a result of the load of the runner during stance, the bottom line is that actual loaded treadmill belt velocity will still be lower than unloaded velocity. On the treadmill used in this study, the offset of the unloaded belt velocity (+0.90 %) caused the true running speed to still be 0.62 % higher than the displayed speed setting. This is a measure that can only be calculated individually for each treadmill, but given the results of this study, it does not appear to be an exceedingly important undertaking.

Even though the overall running velocity does not differ significantly, the fluctuation within each step may be useful to explain some of the observed discrepancies in running kinematics and energetics. In order to compare the variation in velocity across various speeds, the absolute amount of variation must be normalized to some baseline measure of speed. Schamhardt et al. (1994) normalized to the displayed belt velocity and Savelberg et al. (1998) normalized to the maximum instantaneous belt velocity. The variation in this study was expressed as a percent of average belt velocity (see Figure 7) which was very close to the displayed setting as discussed above. It is noted that if the maximal velocity was used, the percentage values obtained in this study would be reduced by an average of 0.14 %.

The percent variation in belt velocity was clearly shown to be dependant on the two independent variables manipulated in this study. The TBM of the subject accounted for 85.8 % of the variance and the treadmill belt speed accounted for a further 9.7 % as determined by linear regression analysis (see Table 3). The strong positive relationship between percent variation and TBM can be easily explained by the direct increase in the horizontal forces applied by the runner. The slight negative relationship between percent variation and treadmill speed is likely a function of the decrease in time over which retarding frictional forces can act. This is in contrast to the weak positive relationship between speed and percent variation found by Savelberg et al. (1998). However, the two speeds used in that study actually compared mode of locomotion since one was a walking trial and the other was a running trial. In running, the horizontal forces do not partially cancel out like they do during the double support phase found in walking, which can explain the increase in percent variation observed here. Since only one treadmill was used in the present study, no comment can be made with respect to the power of the treadmill motor, the main variable that was found to effect belt velocity variation in Savelberg's study. The greater range of values in the remaining variables in this study accounted for the greater predictive ability of the linear regression equation.

5.3 Model Validation

Previous studies have cited the inability to determine horizontal ground reaction forces on the treadmill as an impediment to the elucidation of power transfers between the belt and subject during treadmill running. Estimation of the power transfer has been restricted to the use of comparative overground horizontal ground reaction force values. If it is expected that the fluctuation will cause changes in the kinematics of running, then it seems somewhat counterintuitive to use force measures that do not reflect these changes. It was the aspiration of this study to obtain a more appropriate measure of the horizontal belt reaction force.

The validation of the model used to obtain horizontal reaction forces was not entirely promising (see Figures 8 & 9). The typical negative-positive fore-aft force trace was generally seen, but an overlying higher frequency noise with a magnitude of as much as hundreds of newtons was also present. This noise was similar to that found by Bobbert et al. (1991). However, they applied this procedure to the vertical reaction force which reached a magnitude of 2000 N compared to the maximal horizontal force of about 400 N in this study, so the same absolute error did not confound their signal to the same extent.

The odd rebound of the negative reaction force during the first half of stance was the most remarkable systematic error in the signal. The anticipated single negative phase seems to be separated by a reduction in the magnitude of the calculated signal. From the segmental contributions to the horizontal force in Figure 10, it appears that this was caused by the right thigh or trunk & head segment, or both. Two explanations are offered for this outcome. First, it is possible that skin movement under the markers contributed to the noise in the calculated force. Since there is typically a sharp spike of force on impact, this spike may instead be characterized by dampened wobbling of the skin with respect to the underlying bone. Alternately, inadequate determination of the acceleration of the head and trunk segment may have contributed to this error. This "rigid" segment was calculated using markers on the right hip and on the seventh cervical vertebrae, so any loss of rigidity occurring in the lumber region or the cervical region would result in accelerations not detected by the markers used. For example, extension of the neck and flexion of the trunk in the lumbar region during the region in question would result in a deceleration of the head and lumbar spine that would not be recorded in the hip and seventh cervical markers. It is suggested that inclusion of lumbar and head markers may be necessary to adequately model the head and trunk segment.

In contrast, the markers on the upper extremities can be eliminated. Not only is the magnitude of their contribution to the horizontal force is very small, they also entirely cancel out. The original intent in the present study was to determine the left upper extremity accelerations separately, but given the high rate of marker disappearance, bilateral symmetry was assumed to obtain these accelerations. It should be noted that in the horizontal direction, this is an adequate assumption since the action is perfectly anti-phase with only minor individual deviations. Of course, having the two segments perfectly anti-phase meant that their contributions to the horizontal force are completely cancelled out. These markers can, therefore, be put to better use on the trunk segment.

Variation in the cutoff frequency was unsuccessful in producing a better signal. There did not seem to be a cutoff frequency that would sufficiently eliminate the signal noise without compromising the true signal. In the study by Bobbert et al. (1991), the set of filtering frequencies used (50 Hz for extremities, 20 Hz for hip and 15 Hz for trunk) were found to best preserve the sharp force peak after impact while still adequately removing the noise from the rest of the signal. At a cutoff frequency of 10 Hz, as used in this study, the high frequency peak was lost but the noise in the rest of the signal was reduced. Since high frequencies were not expected to be a major component of the horizontal force, the 10 Hz cutoff frequency seemed to be the best choice.

Despite the generally poor correlation between the calculated and measured horizontal reaction force as seen in figures 8 and 9, the middle portion of the stance showed the least amount of error. As will be discussed in Section 5.5, it was this portion of the force curve that had the greatest effect on the calculation of power. Indeed, the instant that the horizontal force changes from a negative to positive is influential on the implications of the power transfer. It should be noted that the data from Figure 8 was obtained from a faster velocity than the treadmill velocities used in this study, while the velocity in Figure 9, for which the middle portion is more accurately predicted, was within the range of treadmill running speeds. As a result, the power transfer estimated using the calculated horizontal forces will still have informative value.

5.4 Horizontal Force

The horizontal force traces as calculated on the treadmill show two main features; consistency within and variation between subjects (See Figure 11, 12 and Appendix B). This implies that even if the absolute values are not exact, comparisons between speeds and to certain extent between subjects can still be made. The variation between subjects may, however, represent systematic error in the calculation of the horizontal force. These systematic errors could be a result of incorrect segment masses, variable wobbling mass, and inaccuracies in marker placement on joint centres.

Within each subject, the force traces showed a gain in amplitude as the speed increased. This was expected since the horizontal component of the ground reaction force increases to maintain higher speeds (Margaria, 1976). Another interesting finding was the small but consistent shift of the negative-to-positive crossover later in time as speed increased. A possible explanation involves the corresponding increase in treadmill belt fluctuation that was observed as discussed in Section 5.2. The more the belt slows down, the longer it takes for the CM to progress over the base of support during the first half of stance and as the belt sped back up and away from the CM during the second half of stance, this length of time is decreased. This is contrasted by overground running in which there is no appreciable change in the velocity of the ground during contact, and the relative lengths of phases would not be altered. Refer to Section 5.7 for a more detailed discussion of the interactions between velocity, force and work.

The variation between subjects revealed a certain amount of sensitivity in the F_x calculation. The variation during the eccentric phase can be attributed in part to differences in running style. For instance, the subject with a mass of 89.3 kg displayed a running style with short, quick steps, little vertical displacement and a 'jolt' on impact resulting in higher amplitude of the eccentric force. Individual differences will be discussed in more detail in Section 5.7. During the concentric phase, inter-subject variation can be explained by the proportional increase in force with increases in mass as described by Newton's second law (Equation 6). Admittedly, the greater variation in the eccentric phase relative to the concentric phase is likely suggestive of error in the calculated F_x from skin and tissue movement resulting from the impact of right heel contact. This acknowledgment is supported by the fact that subjects with higher BMI displayed greater fluctuation. Another source of this inter-subject variability is the use of average values for segmental masses as found in the literature. (Winter, 1990). Nevertheless, power estimates using these calculated forces may still offer some insight into the effects of the independent variables used in this study.

5.5 Kinetic Energy

In order to determine the relative importance of the work of the treadmill on the runner, a relevant measure of total work is required. Since the work done on the foot by the treadmill occurred in the x-direction, the change in horizontal linear kinetic energy of the CM with respect to the foot was used as this baseline measure. This measure was used by Bourdin et al. (1995) and takes into account the velocity of the CM and the velocity of the belt both in the lab frame of reference. It is acknowledged that this measure alone does not describe the total external work of running, which would require the inclusion of the external work in the vertical direction against gravity.

The accuracy of this measure can be illustrated through comparison to literature values and by the effect of the independent variables used in this study. Bourdin et al. reported an average absolute value for maximum change in kinetic energy of 290 J per step for 10 subjects with average mass of 77 kg running at 5.0 m/s. They acknowledged that this value seemed high but they were unable to identify the source of error. The variation in belt speed in their study seemed highly excessive. Since the mean subject mass in this study was 77.7 kg, a comparable value from this study can be obtained by linear extrapolation of the average ΔE_{ecc} values beyond 4.0 m/s (Figure 13) to give approximately 79.2 J. The deviation of these values are likely a result of treadmill and subject differences. Within this study, the values for ΔE_{ecc} and ΔE_{con} have a clear linear relationship across all subjects and speeds with coefficients of determination of 94.1 % and 93.2 %, respectively. The improvement in accuracy of these measures over the horizontal force measures may be attributed to the relatively small amplification of error in the first-order derivative of the x_{CM} which is required for the energy calculation in comparison to the exponential amplification of error that occurs in a second-order derivative which is required for the force calculation.

5.6 Power

Calculation of the instantaneous power transfer of the treadmill to the runner's foot with respect to the initial foot/belt velocity yields a descriptive power measure. It permits the evaluation of questions such as “Once the runner lands, what is the difference in power transfer if the belt does slow down in comparison to if it doesn’t slow down?” and “How does the power transfer affect the eccentric and concentric phases of stance?” Refer to Figure 3 for the following discussion.

Since the power transfer on the treadmill is being compared to overground running in which there is no transfer of this kind, an overground analogy of treadmill running is useful. If the belt velocity slows down (in the negative direction) and then speeds up again during each stance phase, the belt is in effect “sliding” forward during the stance phase and just about coming to a rest again at push off at the same time the runner is traveling forward. Therefore, the amount that the runner must slow down their CM with respect to the lab during the eccentric phase in order to maintain stability is reduced. It follows, then, that the magnitude of force during the concentric phase to speed the CM back up with respect to the lab in order to maintain velocity is also reduced.

The power transfer presented in this study can provide an explanation for this apparent benefit of treadmill velocity fluctuation. The initial phase of negative power is described as energy flow from the foot to the treadmill during the eccentric phase of stance. This flow of energy reduces the amount of energy the muscles must absorb in order to decelerate the body’s CM with respect to the foot. The positive power is described as energy flow from the treadmill to the foot during the concentric phase of stance. This additional energy source reduces the amount of energy the muscles must generate in order to achieve the required acceleration of the CM with respect to the foot.

Previously, it had been suggested that:

> the moving treadmill belt reduces the energy requirements of the runner by bringing the supporting leg back under the body during the support phase of running (Frishberg, 1983).

The explanation given above offers a more precise and accurate account of the relative energetic ease of treadmill running with respect to overground running. Additionally, the proper use of the change in belt velocity (magnitude and direction) that is caused by the foot/belt interaction force in the power calculation needs to be calculated in a kinetic analysis of treadmill locomotion. Winter (1978) hypothesized that:

> if the force acts against the treadmill direction, the energy flows from the treadmill into the body and the motor will tend to slow down. Such a situation occurs at weight acceptance. Conversely, at push-off the horizontal shear force is in the same direction as the belt, which means that energy is flowing from the body to the motor and making it speed up momentarily.

The direction of energy flows at weight acceptance and push-off are in opposition to the findings of this study because the above argument used instantaneous belt speed with respect to the lab. As noted in this study, the treadmill velocity with respect to the lab is simply the magnitude of the moving frame of reference and the resulting power transfer is zero, just like in overground running. The change in belt velocity with respect to the initial velocity at heel contact, which was used in this study, represents any change in belt velocity with respect to this frame of reference which is moving in the negative direction. As a result, the slowing of belt speed is interpreted here as the belt "sliding forward" during weight acceptance and a return to the frame of reference velocity during push-off. This will give the desired power transfer between the runner and the treadmill belt. It should also be noted that the power transfer calculated in this study occurs between the runner and the treadmill belt and does not differentiate between the contribution of the motor and friction between the belt and treadmill bed.

In earlier studies, power transfers were calculated using the change in velocity with respect to average treadmill belt velocity (Schamhardt et al., 1994; Savelberg et al., 1998). Using this method, the power transfer trace displays continual changes between positive and negative power that are difficult to reconcile with intuition. The additional changes in the direction of the power transfer occur at the points at which belt velocity crosses average velocity. It was thought by these authors that power transfers were not entirely relevant and that the time integral (work) was much more meaningful.

3.7 Work

Discussion of the amount of work performed by the treadmill should be qualified by the limitations of the force calculation. Nevertheless, there are some trends evident in the results that may give some insight into the effects of the runner's speed, mass and running style on the magnitude of work contributed by the treadmill.

First of all, the contribution of the treadmill to work performed by the runner during the concentric phase is likely of more importance than the savings during the eccentric phase. Abbot et al. (1952) demonstrated that negative work was more efficient than positive work with his well known cycle ergometer experiment. If we assume that negative work is three times as efficient as positive work, an assumption used by Winter (1978) and Pierrynowski et al. (1980), the average of 3.37 J during the concentric phase

(W_{con}) becomes 10.1 J in comparison to the average of –4.49 J during the eccentric phase (W_{ecc}). Indeed, this reasoning was the motive for separating the stance phase into eccentric and concentric portions for analysis. Since the concentric work done during the push-off phase is responsible for the majority of the energy cost of running, it would seem that the 3.37 J per step is the best indicator of the savings of treadmill running in this study. The magnitude of this work savings is, however, dependent on the choice of frame of reference. In spite of this possible concession, it was an aim of this study to find the most relevant reference frame so that this type of conclusion could be made.

According to previous studies (Schamhardt et al, 1994; Savelberg et al., 1998), another possible interpretation of the data is that the total work per step of –1.12 J (difference between positive and negative work) is the cost savings, a conclusion which is independent of the chosen frame of reference. If one attempts to explain this 1.12 J value in the context of this study, the conclusion would be that more work is saved during the eccentric phase than is that saved during the concentric phase. Such an explanation makes this value seem not entirely meaningful. With this in mind, it may be that the addition of the two magnitudes, giving 7.86 J, may be the savings per step of treadmill running. The interpretation of the results may, therefore be open to discussion. Since the trends in the data are consistent for both phases, the following discussion will not differentiate between the two.

Given the small magnitude of the work done by the treadmill, the absolute differences between subjects are also quite small but at least the relative differences may inspire a need for explanation. Figures 16 and 17 and the coefficients of correlation showed that, in general, the absolute amount of work done by the treadmill increased slightly with increases in TBM and running speed. However, there seems to be a deviation from this trend in the subject with a mass of 66.7 kg and the subject with a mass of 89.3 kg. Investigation of the characteristics of these subjects revealed that their BMI's are above the average (see Table 1).

Two separate interpretations, one for each subject, are offered to reconcile these results with visual observation. The 89.3 kg subject displayed the highest step rate and shortest flight phase (see Appendix A). The short flight phase is the best indication of a relative decrease in the vertical components of the reaction forces and therefore, a relative increase in the horizontal reaction forces to maintain the same speed. A relative increase in the ΔE_{ecc} can also be seen for this subject indicating that more horizontal work was done on the CM (Figure 13). Given that no relative increase in the amount of velocity fluctuation was detected despite these increased horizontal forces (Figure 7), it is suggested that the velocity fluctuation is equally dependent on friction between the belt and treadmill bed which, in turn, is proportional to the vertical forces. In summary, the relative increase in the magnitude of the reaction forces in the horizontal direction increase the magnitude of work that the treadmill can contribute to deceleration and acceleration.

The very low values of work done by the treadmill on the 66.7 kg subject at all speeds was harder to reconcile with visual observation. However, it was expected that the results of this subject would reflect the "powerful" type of running style. The relatively low horizontal forces can be explained by a relative decrease in the amount of rearfoot contact accompanied by more emphasis on pulling the foot back under the CM. This can also be seen in the relatively small ΔE_{ecc} for this subject in comparison to trend displayed the three subjects with below average BMI. In summary, it could be said that this subject did not "recruit" the treadmill to contribute to horizontal work as much as the other subjects.

Expression of the treadmill work with respect to the change in linear kinetic energy preserves the general relationships described above with the exception of the trend with TBM. There is a relative amplification of the lighter subjects in comparison to the heavier subjects. This is reflective of the fact that ΔE_{kin} has a more positive correlation with mass than the corresponding measures of treadmill work. The main significance of this is simply that very little absolute variation in treadmill work was found with the independent variables in this study.

Chapter 6

Conclusions

The main purpose of this study was to investigate the characteristics of treadmill running as they pertain to the velocity fluctuations in the treadmill belt which do not occur overground. It was largely a study in methodology and theoretical implications of the calculated output measures.

Previous studies have shown that variation within each running stride clearly exist (Schamhardt, 1994; Savelberg et al., 1998; Radstake and Dowling, 1999). The device used in this study to capture the instantaneous velocity of the treadmill belt was shown to be very accurate by a number of accounts. The average velocity of the runner was shown to be well represented by the displayed setting on the treadmill used in this study. As for the belt speed fluctuation within each stride, the purpose of this study was to use a wide range of values for the main variables that have been shown to effect the belt speed variation within each stride. As a result, subject mass was shown to account for 85.8 % of the variance in the dependant measure while running speed explained an additional 9.7 %. Although only one treadmill was used in this study, the strong linear relationship between subject mass and running speed can be assumed to also manifest a similar linear relationship on other treadmills.

The primary limitation in the elucidation of a measure of work contributed by the treadmill as a result of this speed variation has been the determination of the causative forces. Previous studies have determined this horizontal power transfer using forces obtained during overground running at approximately the same speed (Savelberg et al., 1998). If the actual forces occurring between the treadmill and the runner could be obtained, then one would not need to make the assumption that treadmill and overground running forces are similar in order to show that the power transfer is different. The second purpose of this study was therefore, to obtain a relevant measure of the horizontal reaction forces by working backwards from the observed change in positional data (Bobbert et al., 1991).

Although sound in theory, the sources of error in the calculation were too great to get a more accurate measure of the horizontal reaction force. Despite these inaccuracies, the measure was still sensitive to differences between subject mass, running style and running speed. As a result, the force measures obtained could still be used to illustrate differences between subjects and running speeds and permit a discussion of the estimated horizontal power transfers with the treadmill. The values obtained for the horizontal work performed by the treadmill make intuitive sense as well. Since the belt velocity variation was between 4.2 % and 8.6 % of belt velocity, a correspondingly small measure of work done as a result of this fluctuation was expected. The average values of horizontal work in this study were 4.49 J done by the runner on the treadmill during the eccentric phase and 3.37 J done by the treadmill on the runner during the concentric phase. The external work done on the treadmill during the eccentric phase directly reduces the amount of internal muscular work the runner must do in order to decelerate himself. Since the work done during the concentric phase of gait is responsible for most of the energetic cost of running, it is suggested that the average of 3.37 J, or 10.15 % of the change in horizontal kinetic energy, is the measure of savings in the horizontal direction during treadmill running in comparison to overground running. A similar savings may, indeed, be realized in the vertical direction (McMahon and Greene, 1979) given the cushioning properties of a treadmill, and this should be investigated in further research.

The most unique contribution of this study may be in the determination of a method for calculating power transfers that have a descriptive capacity. By dividing the stance phase into eccentric and concentric portions, the contribution of treadmill power to that specific phase can be explained. Also, by using a measure of velocity in this calculation which reflects the change that occurs over this period, only negative power is found during the eccentric phase and only positive power during the concentric phase. This power transfer can then be described as flowing from the runner to the belt during the eccentric phase and flowing from the belt to the runner in the concentric phase. The benefit of this energy flow is evident in a reduction of the amount of energy the runner must absorb during deceleration and another reduction in the amount of energy the runner must generate as they attempt to accelerate again. As better equipment becomes available and treadmill force measures are improved, it is this calculation of power that should be used for a relevant and descriptive discussion of the results.

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APPENDIX A

Kinematic Variables: Timing and Velocity

STANCE TIME (ms)

Subject	Trial			
	2.7 m/s	3.1 m/s	3.6 m/s	4.0 m/s
55.2	290	268	250	232
66.7	313	288	256	237
77.7	341	301	283	247
89.3	308	280	265	243
99.6	344	303	280	292
Average	319.2	288	266.8	250.2
SD	22.95	14.646	14.481	24.056

STEP TIME (ms)

Subject	Trial			
	2.7 m/s	3.1 m/s	3.6 m/s	4.0 m/s
55.2	408	378	374	361
66.7	367	354	342	335
77.7	408	393	374	361
89.3	371	335	329	323
99.6	403	381	362	385
Average	391.4	368.2	356.2	353
SD	20.599	23.339	20.055	24.372

STANCE AVG BELT VELOCITY (m/s)

Subject	Trial			
	2.7 m/s	3.1 m/s	3.6 m/s	4.0 m/s
55.2	2.687	3.139	3.647	4.018
66.7	2.72	3.222	3.574	4.018
77.7	2.694	3.128	3.558	4.019
89.3	2.687	3.128	3.561	4.002
99.6	2.701	3.122	3.58	4.02
Average	2.6978	3.1478	3.584	4.0154
SD	0.0137	0.0419	0.0364	0.0075

RIGHT STEP AVG BELT VELOCITY (m/s)

Subject	Trial			
	2.7 m/s	3.1 m/s	3.6 m/s	4.0 m/s
55.2	2.706	3.149	3.576	4.044
66.7	2.728	3.159	3.591	4.039
77.7	2.708	3.154	3.581	4.05
89.3	2.685	3.141	3.58	4.028
99.6	2.717	3.144	3.607	4.045
Average	2.7088	3.1494	3.587	4.0412
SD	0.0159	0.0073	0.0125	0.0083

UNLOADED AVG BELT VELOCITY (m/s)

Subject	Trial			
	2.682	3.129	3.576	4.023
55.2	2.709	3.149	3.6	4.058
66.7	2.728	3.15	3.61	4.044
77.7	2.693	3.152	3.606	4.071
89.3	2.711	3.148	3.618	4.065
99.6	2.703	3.16	3.615	4.065
Average	2.7088	3.1518	3.6098	4.0606
SD	0.0128	0.0048	0.0072	0.0104
% BIAS	0.9993	0.7287	0.9452	0.9346

RUNNER'S AVG BELT VELOCITY (m/s)

Subject	Trial			
	2.7 m/s	3.1 m/s	3.6 m/s	4.0 m/s
55.2	2.698	3.156	3.577	4.046
66.7	2.721	3.152	3.584	4.033
77.7	2.707	3.152	3.576	4.049
89.3	2.708	3.148	3.588	4.038
99.6	2.703	3.161	3.615	4.065
Average	2.7074	3.1538	3.588	4.0462
SD	0.0086	0.0049	0.0159	0.0123

STANCE RANGE IN BELT VELOCITY (m/s)

Subject	Trial			
	2.7 m/s	3.1 m/s	3.6 m/s	4.0 m/s
55.2	0.1179	0.1358	0.1635	0.1692
66.7	0.1575	0.1692	0.1801	0.179
77.7	0.1847	0.1912	0.1952	0.2337
89.3	0.2163	0.2225	0.2296	0.2457
99.6	0.2334	0.2446	0.2681	0.298
Average	0.182	0.1926	0.2073	0.2251
SD	0.0462	0.043	0.0418	0.0526

SWING RANGE IN BELT VELOCITY (m/s)

Subject	Trial			
	2.7 m/s	3.1 m/s	3.6 m/s	4.0 m/s
55.2	0.0099	0.0142	0.028	0.0299
66.7	0.0128	0.0062	0.0111	0.0211
77.7	0.0188	0.0202	0.0258	0.0444
89.3	0.0229	0.0177	0.032	0.0484
99.6	0.0033	0.0229	0.0268	0.03
Average	0.0135	0.0162	0.0247	0.0348
SD	0.0076	0.0065	0.008	0.0113

STANCE RANGE IN BELT VELOCITY (%)

Subject	Trial			
	2.7 m/s	3.1 m/s	3.6 m/s	4.0 m/s
55.2	4.3862	4.325	4.4842	4.212
66.7	5.7908	5.2506	5.0392	4.4541
77.7	6.8577	6.1126	5.4854	5.8154
89.3	8.0485	7.1121	6.4485	6.1397
99.6	8.6405	7.8355	7.4878	7.4129
Average	6.7448	6.1272	5.789	5.6068
SD	1.716	1.4058	1.1914	1.3099

SWING RANGE IN BELT VELOCITY (%)

Subject	Trial			
	2.7 m/s	3.1 m/s	3.6 m/s	4.0 m/s
55.2	0.3647	0.45	0.7827	0.7402
66.7	0.4683	0.1953	0.3081	0.5231
77.7	0.6956	0.6395	0.7191	1.0973
89.3	0.8516	0.5632	0.8944	1.2028
99.6	0.1212	0.7295	0.7432	0.7409
Average	0.5003	0.5155	0.6895	0.8609
SD	0.2849	0.2063	0.2235	0.281

RANGE / VELOCITY / MASS (%)

Subject	Trial			
	2.7	3.1	3.6	4.0
55.2	0.079	0.078	0.081	0.076
66.7	0.087	0.079	0.076	0.067
77.7	0.088	0.079	0.071	0.075
89.3	0.09	0.08	0.072	0.069
99.6	0.087	0.079	0.075	0.074
Average	0.086	0.079	0.075	0.072
SD	0.004	5E-04	0.004	0.004

Regression Summary for Dependent Variable: %VARIATION

R= .97761040 R^2= .95572210 Adjusted R^2= .95051294

F(2,17)=183.47 p<.00000 Std.Error of estimate: .30615

	BETA	St. Err. of beta	B	St. Err. of B	t(17)	p-level
Intercpt			2.758	0.574	4.805	2E-04
MASS	0.926	0.051	0.079	0.004	18.147	1E-12
SPEED	-0.313	0.051	-0.840	0.137	-6.135	1E-05

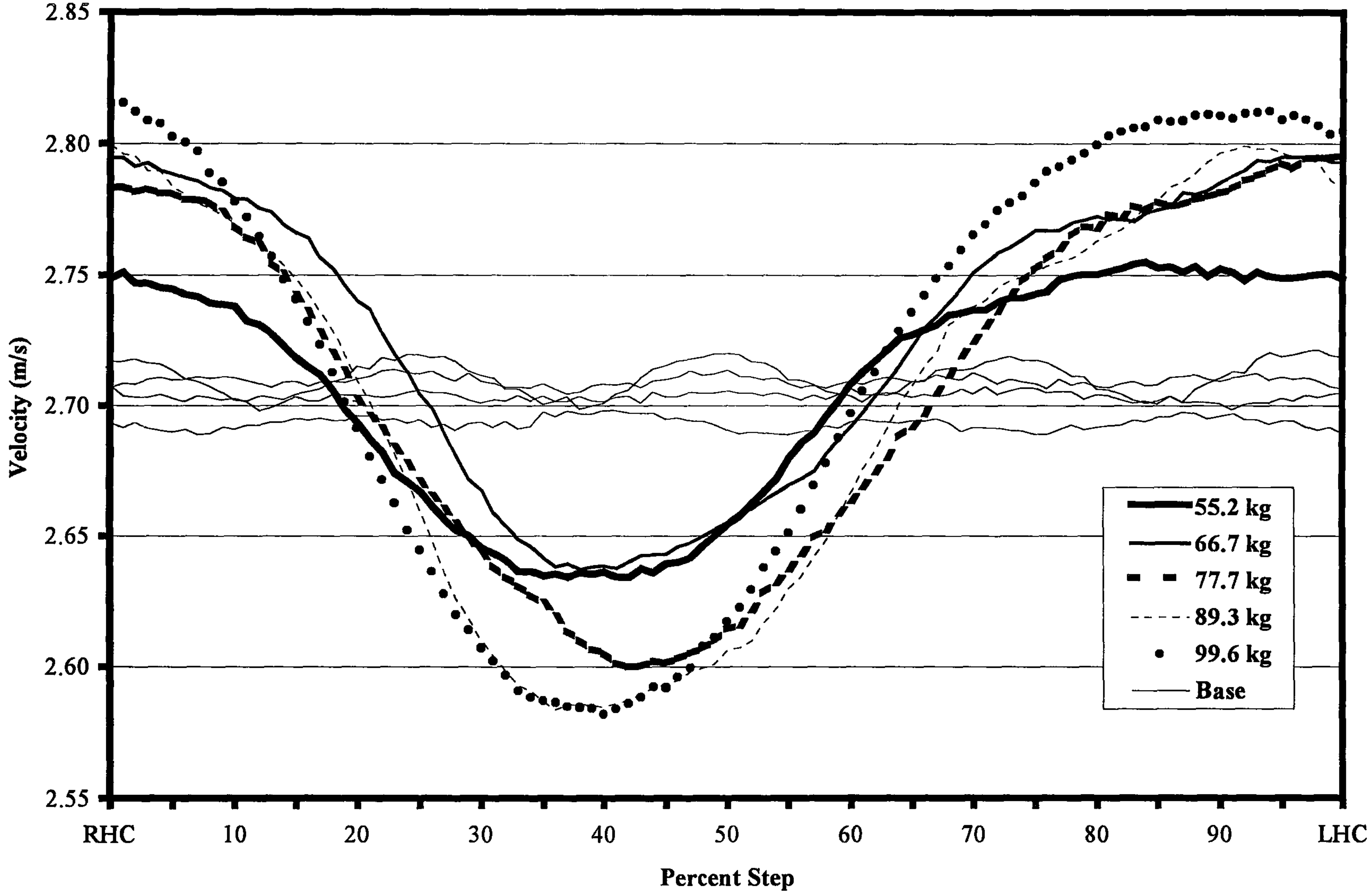

Figure A-1. Instantaneous Treadmill Belt Velocity for all Subjects and Baselines at the 2.7 m/s Setting

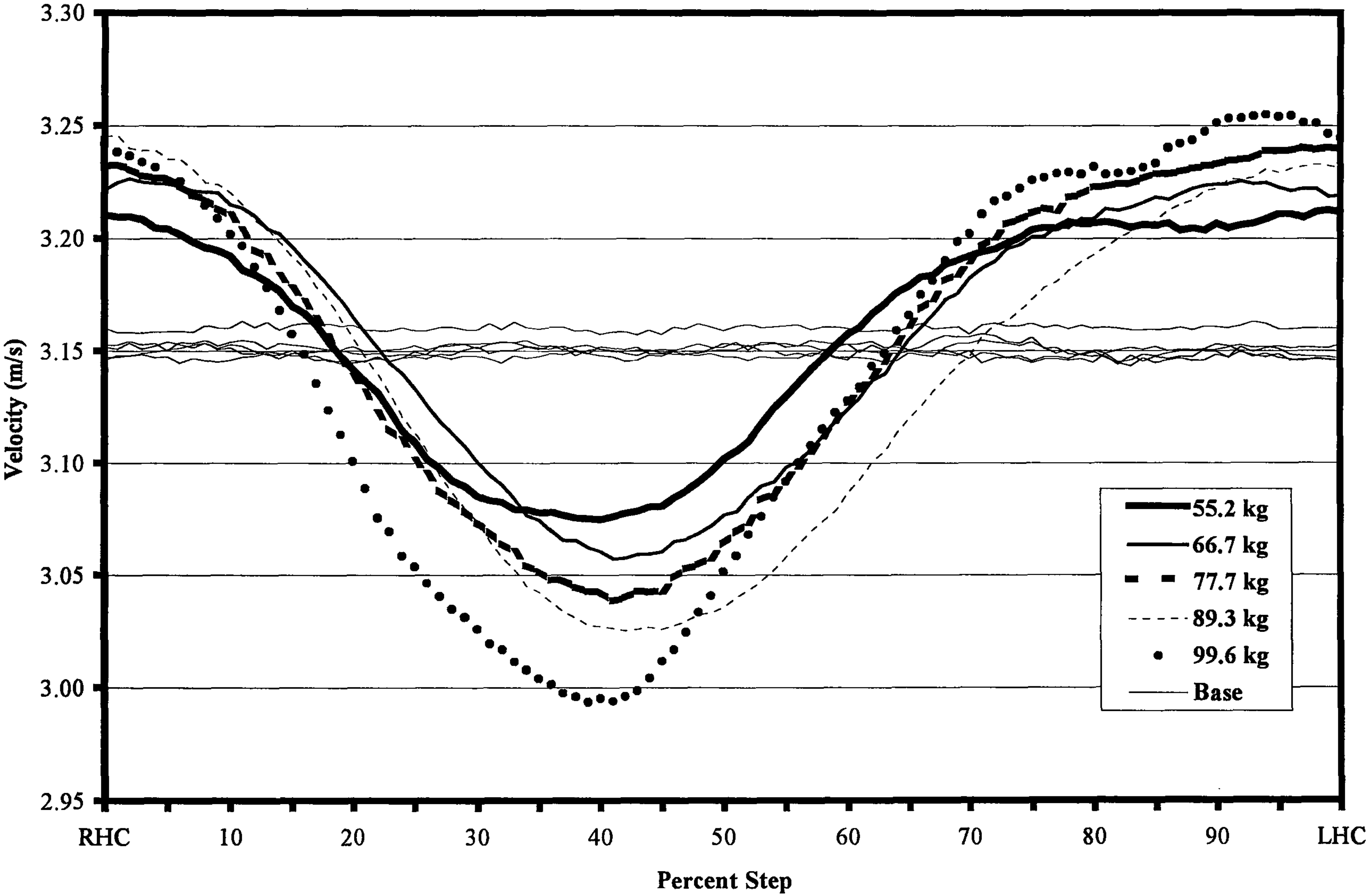

Figure A-2. Instantaneous Treadmill Belt Velocity for all Subjects and Baselines at the 3.1 m/s Setting

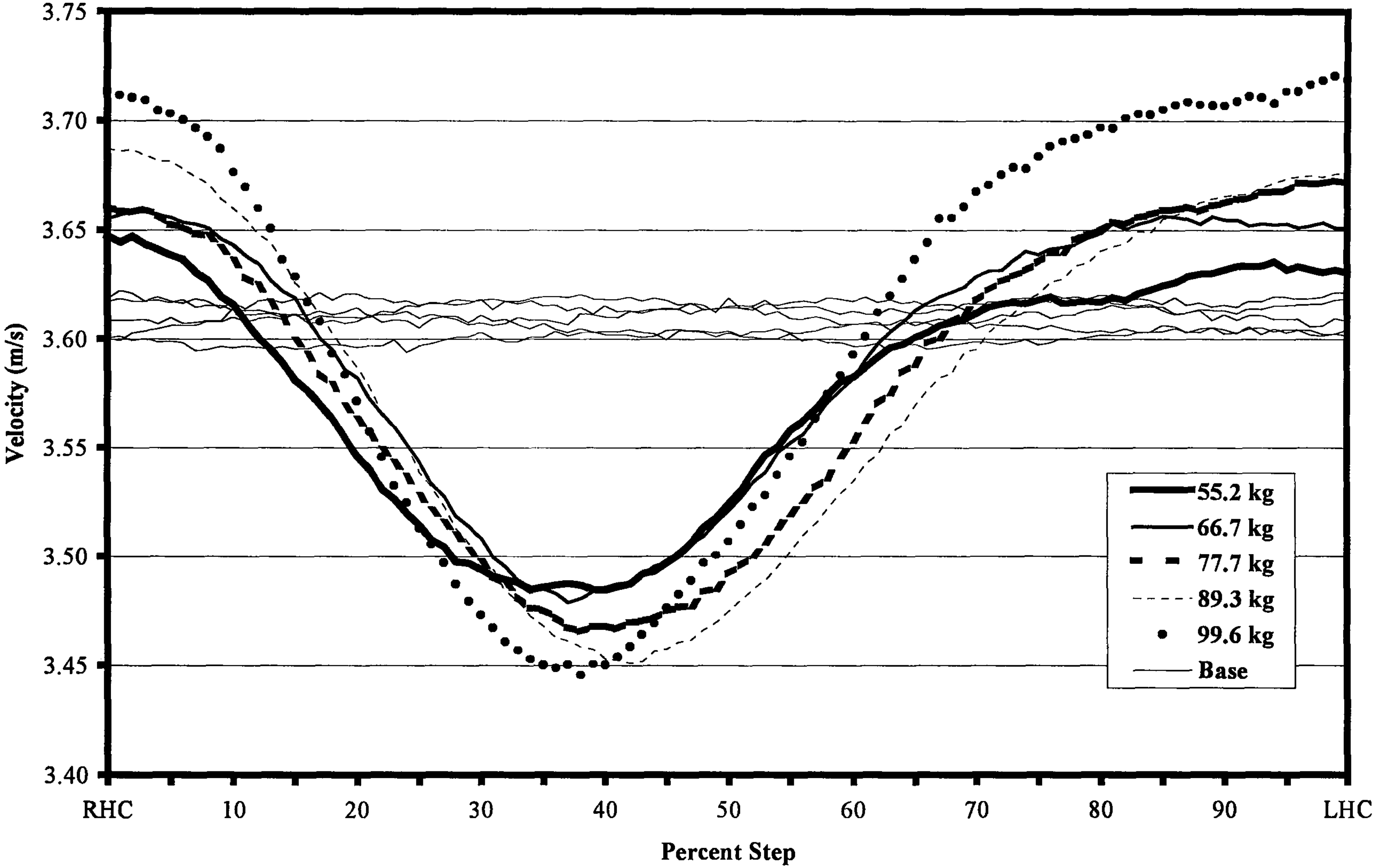

Figure A-3. Instantaneous Treadmill Belt Velocity for all Subjects and Baselines at the 3.6 m/s Setting

APPENDIX B

Horizontal Reaction Forces

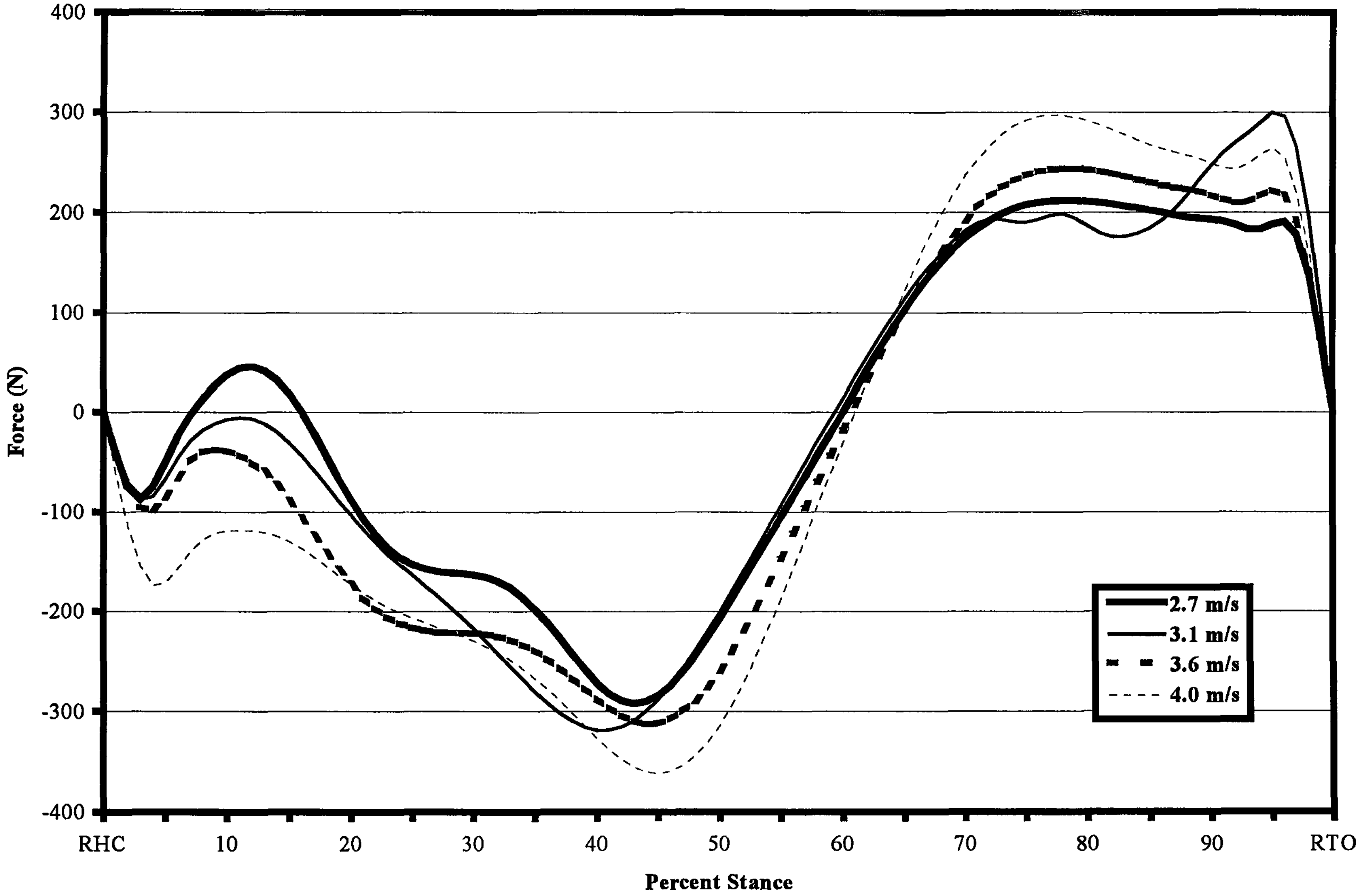

Figure B-1. Horizontal Reaction Forces for the 55.2 kg Subject at all Speeds

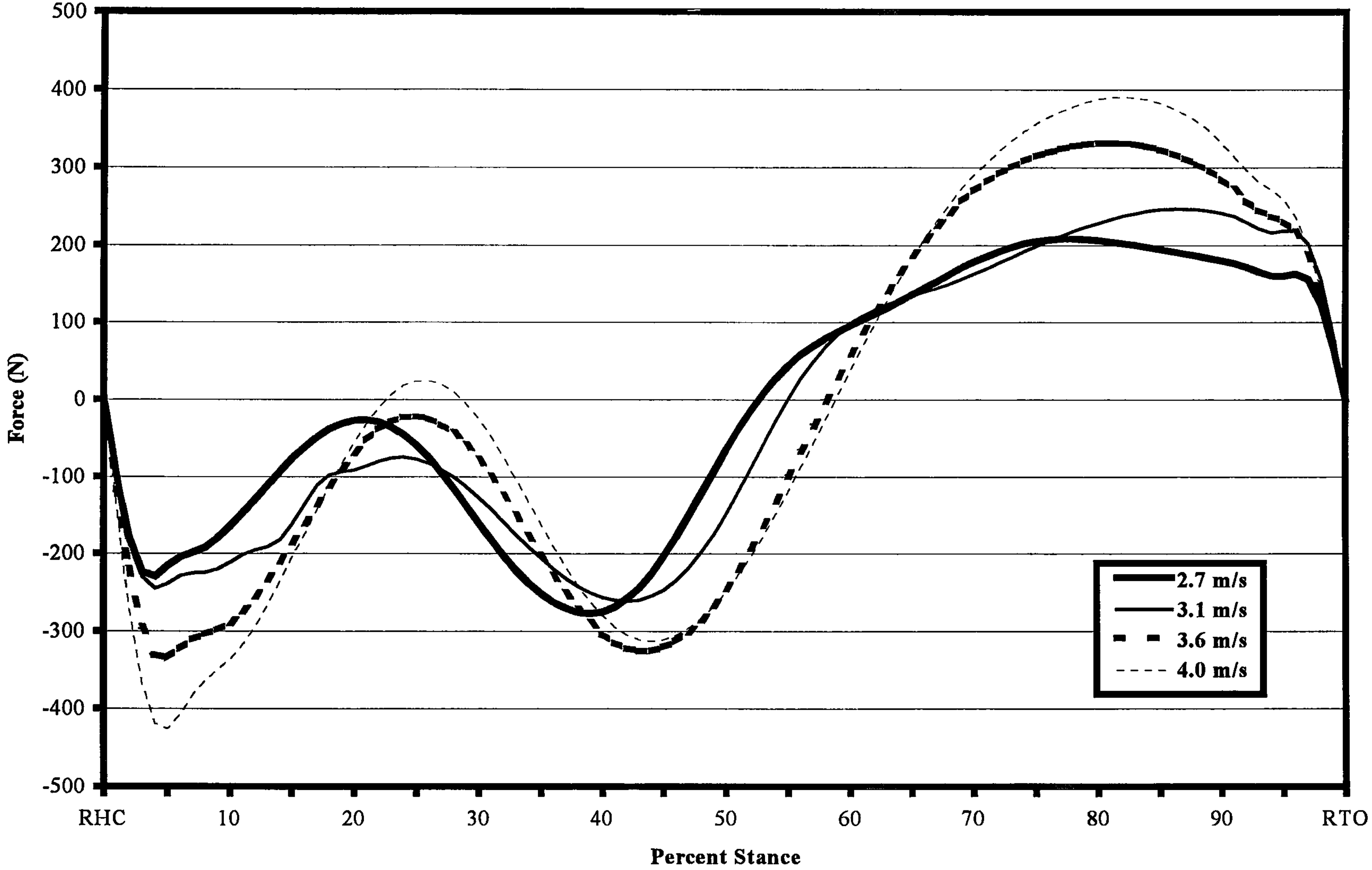

Figure B-2. Horizontal Reaction Forces for the 66.7 kg Subject at all Speeds

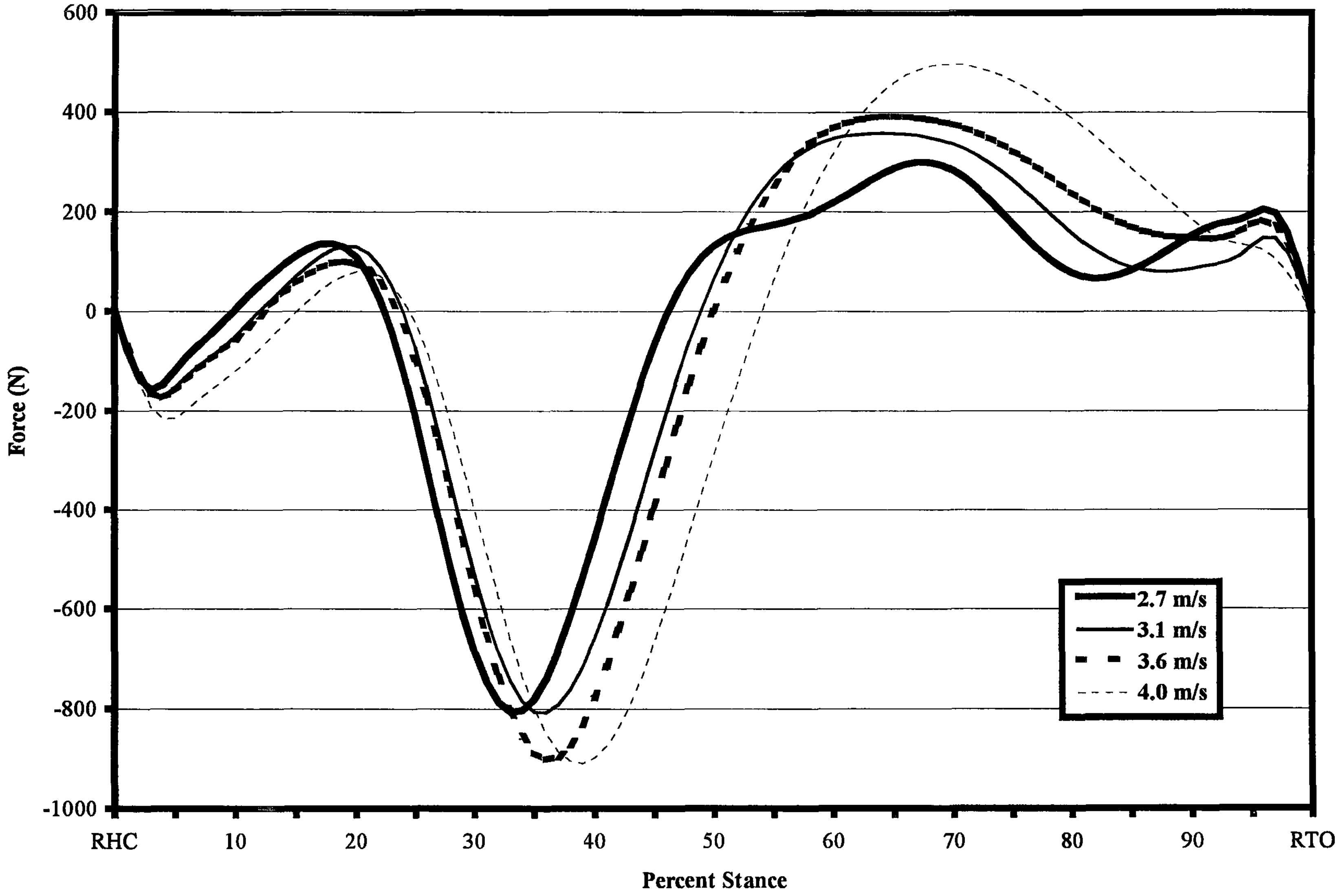

Figure B-3. Horizontal Reaction Forces for the 89.3 kg Subject at all Speeds

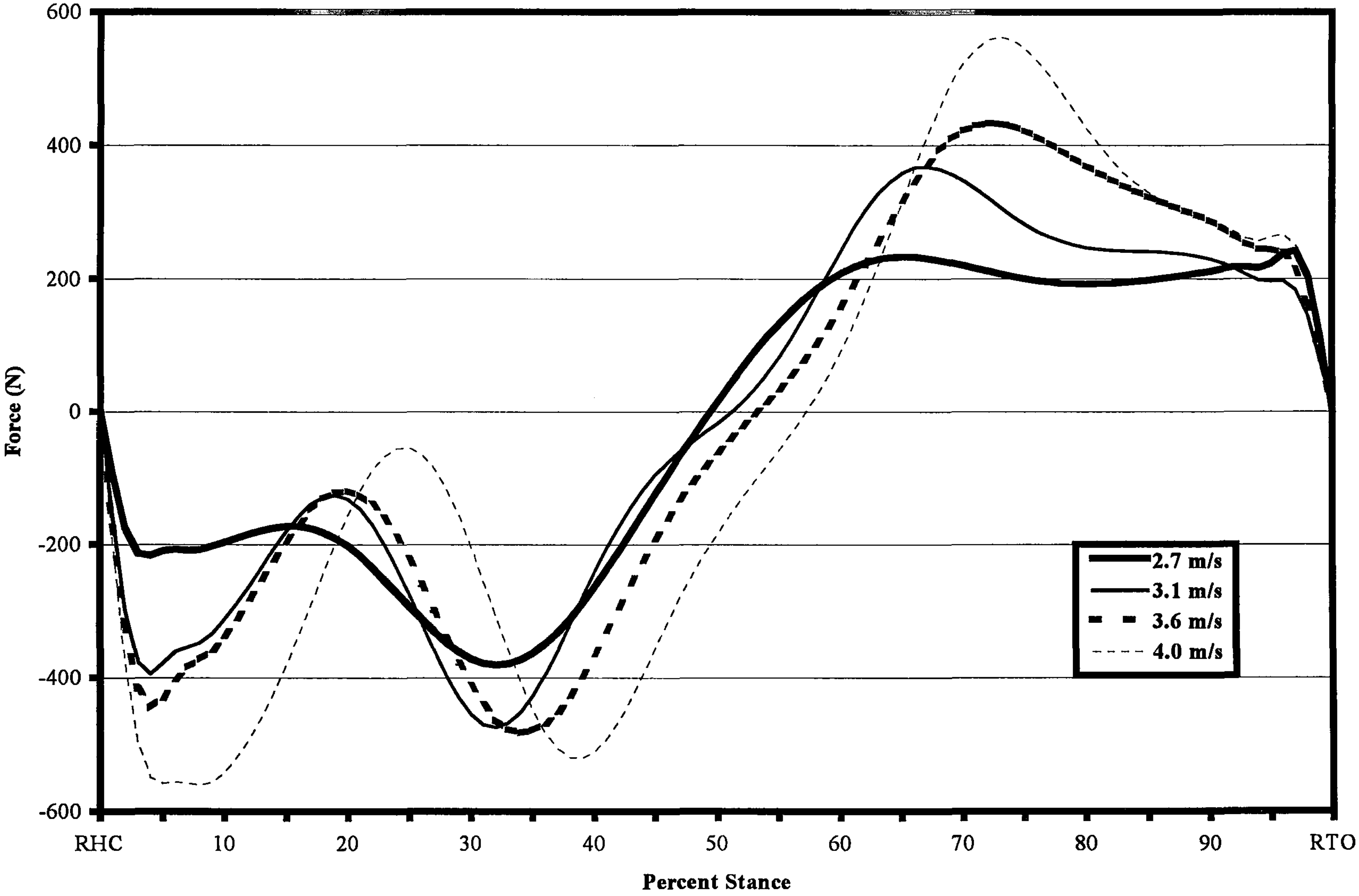

Figure B-4. Horizontal Reaction Forces for the 99.6 kg Subject at all Speeds

APPENDIX C

Treadmill Power

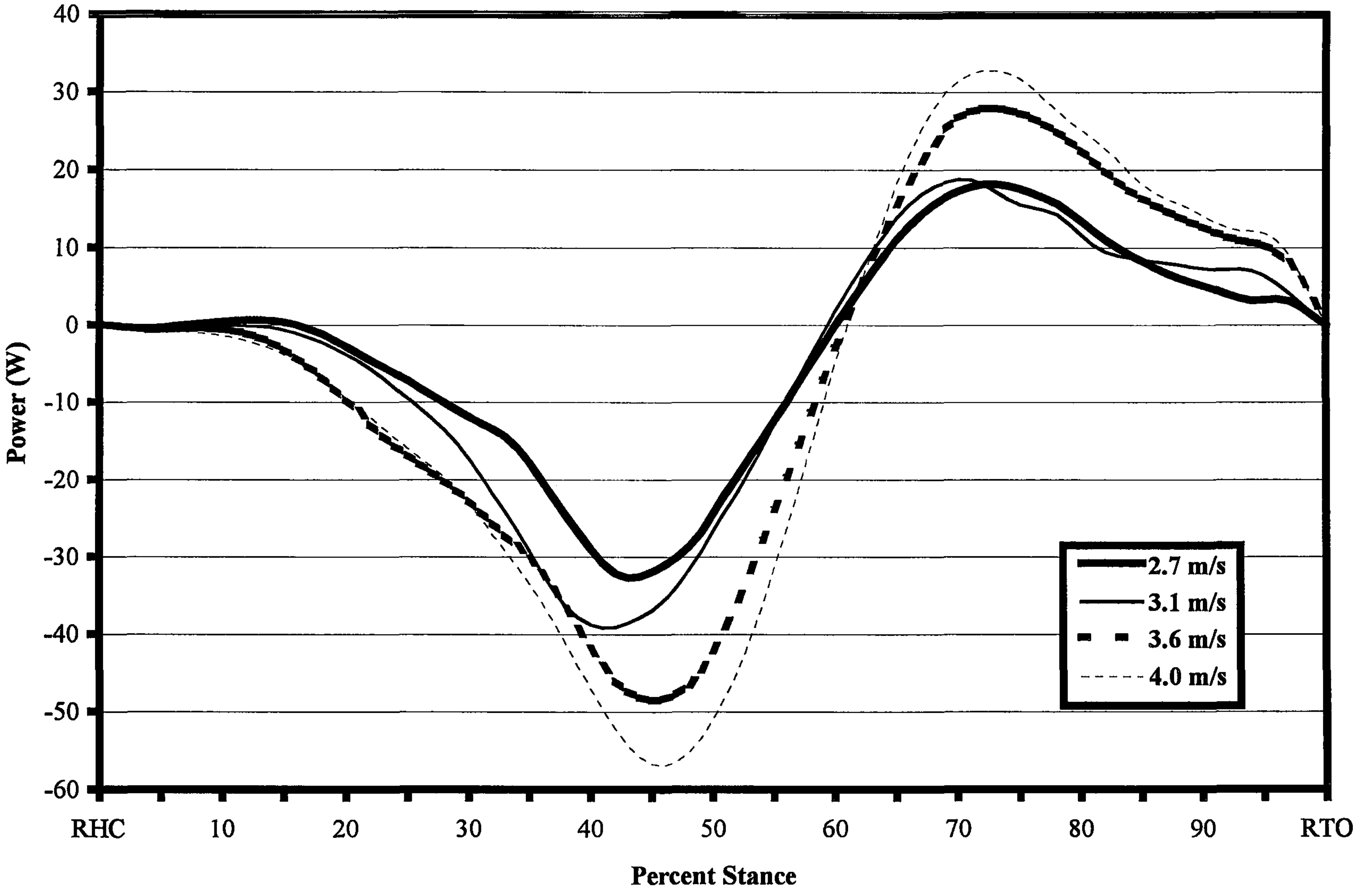

Figure C-1. Treadmill Power Calculations for the 55.2 kg Subject at all Speeds

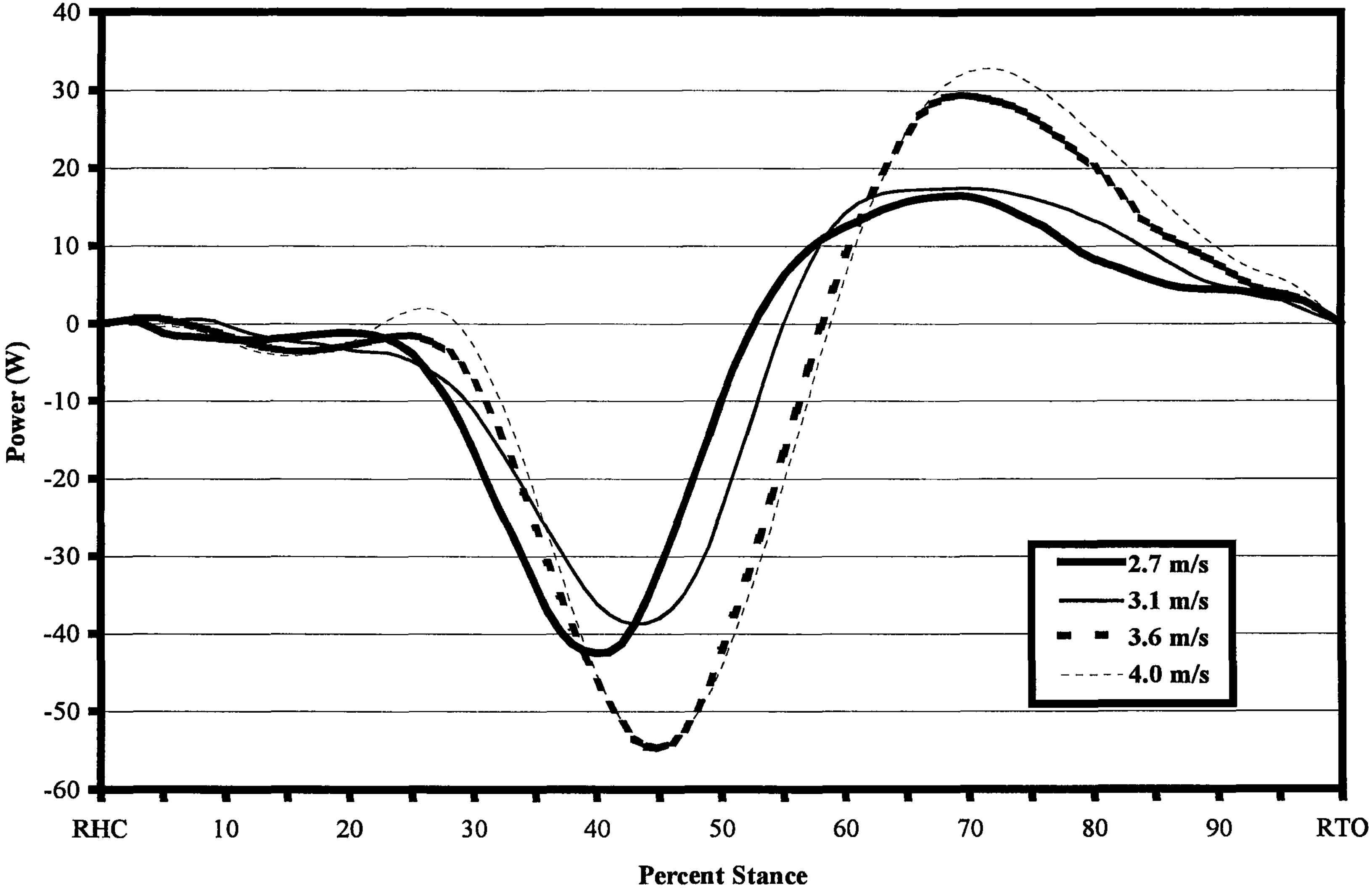

Figure C-2. Treadmill Power Calculations for the 66.7 kg Subject at all Speeds

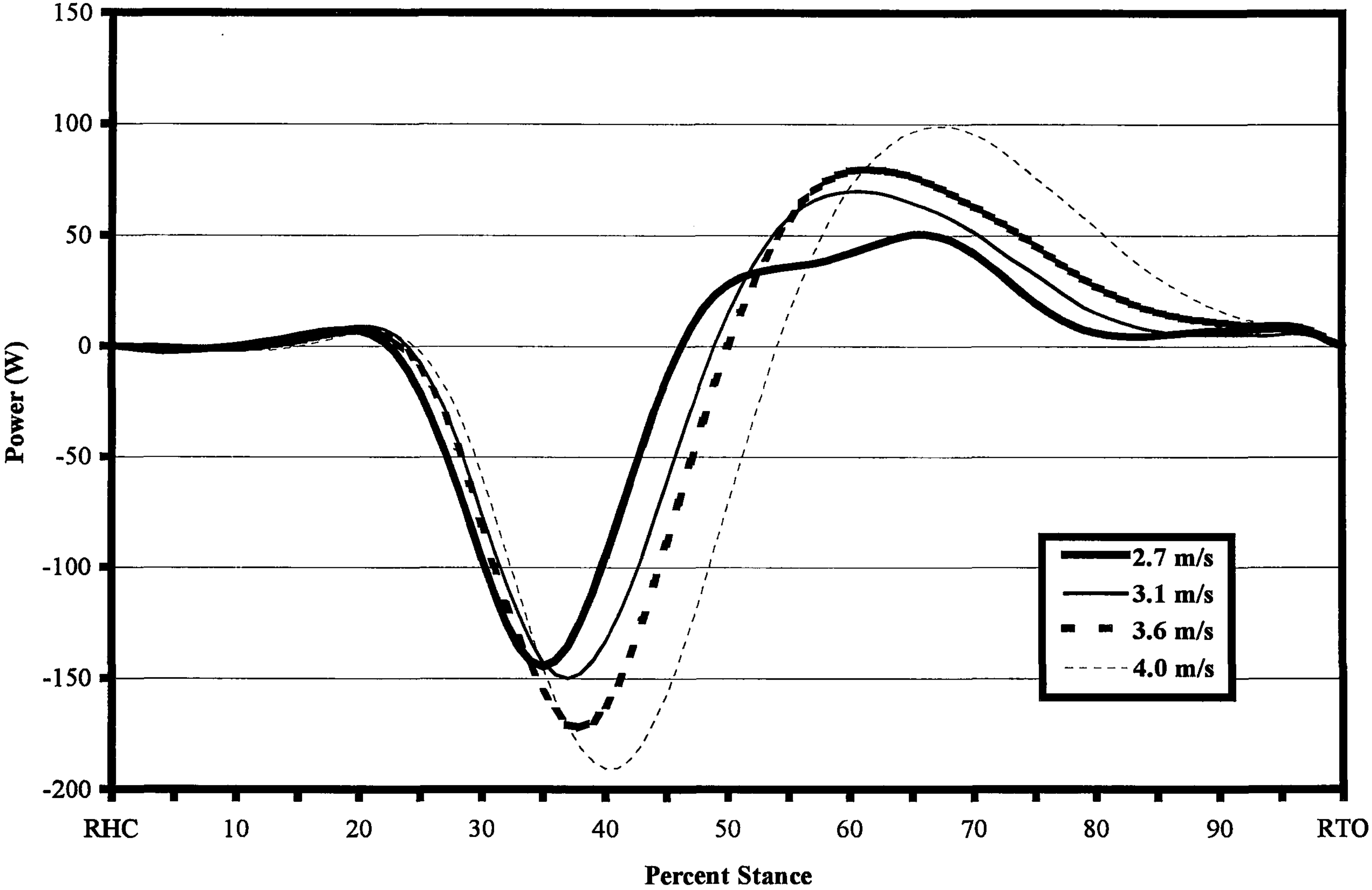

Figure C-3. Treadmill Power Calculations for the 89.3 kg Subject at all Speeds

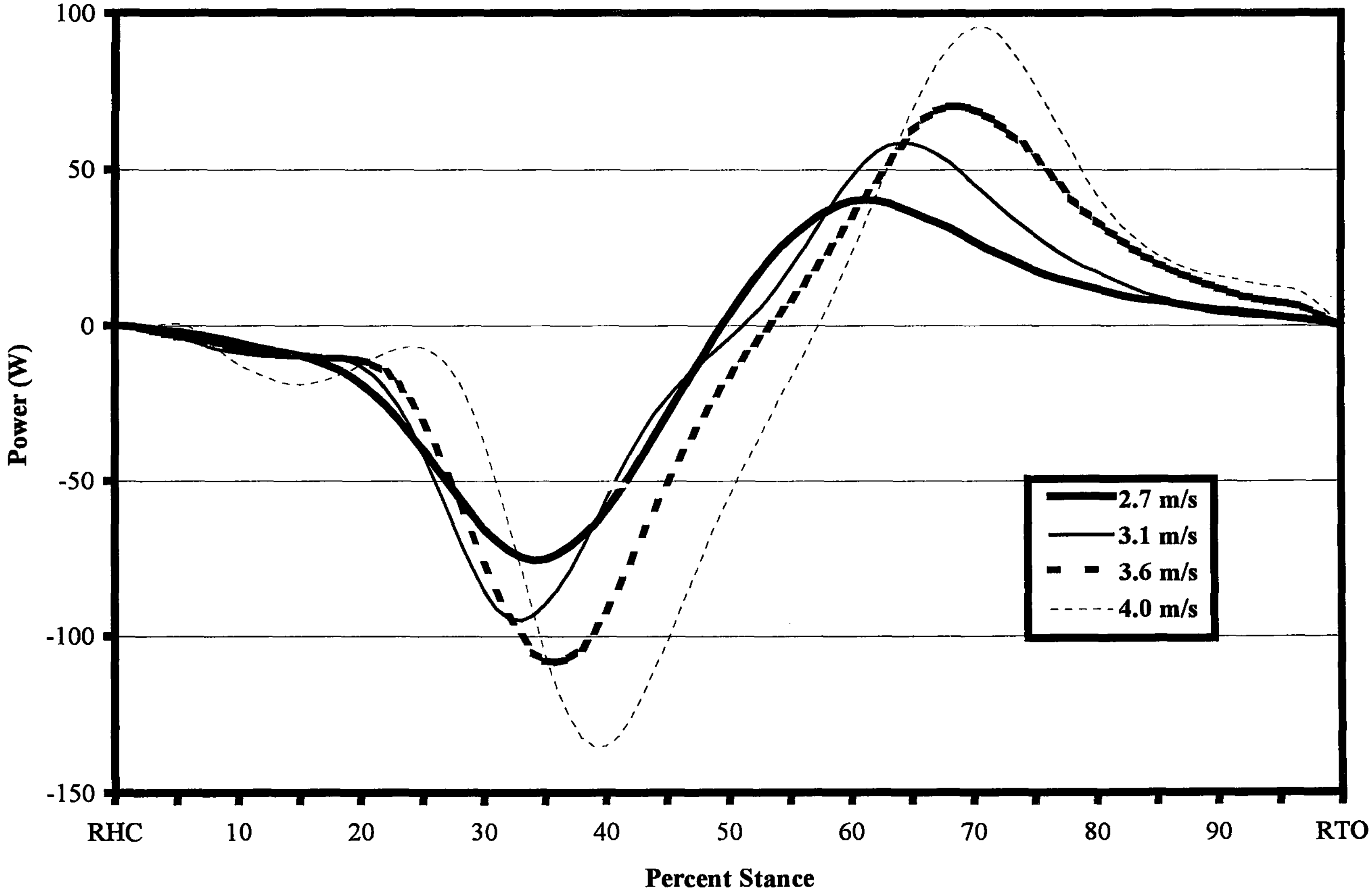

Figure C-4. Treadmill Power Calculations for the 99.6 kg Subject at all Speeds

APPENDIX D

Treadmill Work and Kinetic Energy Regression Tables

Regression Summary for Dependent Variable:
ΔEecc
R= .96981017 R^2= .94053177 Adjusted R^2= .93353551
F(2,17)=134.43 p<.00000 Std.Error of estimate: 6.0774

	BETA	St.Err.of BETA	B	St. Err. of B	t(17)	p-level
Intercpt			114.97567	11.39536	10.08969	0.00000
MASS	-0.90724	0.05915	-1.32291	0.08624	-15.33925	0.00000
SPEED	-0.342706	0.059145	-15.75587	2.719182	-5.794342	2.16E-05

Regression Summary for Dependent Variable: Wecc
R= .73336524 R^2= .53782458 Adjusted R^2= .48345100
F(2,17)=9.8913 p<.00142 Std.Error of estimate: 1.1379

	BETA	St.Err.of BETA	B	St. Err. of B	t(17)	p-level
Intercpt			4.25890	2.13360	1.99611	0.06220
MASS	-0.62284	0.16488	-0.06100	0.01615	-3.77747	0.00150
SPEED	-0.38715	0.16488	-1.19544	0.50912	-2.34804	0.03123

Regression Summary for Dependent Variable: %Wecc
R= .73891407 R^2= .54599401 Adjusted R^2= .52077145
F(1,18)=21.647 p<.00020 Std.Error of estimate: 3.8696

	BETA	St.Err.of BETA	B	St. Err. of B	t(18)	p-level
Intercpt			31.6935	4.35362	7.279804	9.14E-07
MASS	-0.738914	0.1588161	-0.255492	0.054913	-4.652639	0.000198

Regression Summary for Dependent Variable: %WECC
R= .76062611 R^2= .57855208 Adjusted R^2= .52896998
F(2,17)=11.669 p<.00065 Std.Error of estimate: 3.8364

	BETA	St.Err.of BETA	B	St. Err. of B	t(17)	p-level
Intercpt			43.26667	10.98252	3.93959	0.00106
MASS	-0.60996	0.19353	-0.21090	0.06692	-3.15180	0.00582
%STANCE	-0.221781	0.1935278	-0.196564	0.171523	-1.145993	0.267674

Regression Summary for Dependent Variable:
ΔEcon
R= .96545619 R^2= .93210565 Adjusted R^2= .92411808
F(2,17)=116.69 p<.00000 Std.Error of estimate: 5.6063

	BETA	St.Err.of BETA	B	St. Err. of B	t(17)	p-level
Intercpt			-88.36341	10.51199	-8.40597	0.00000
MASS	0.93280	0.06320	1.17430	0.07956	14.76032	0.00000
SPEED	0.248981	0.0631964	9.882562	2.50839	3.939803	0.001056

Regression Summary for Dependent Variable: Wcon
R= .74057475 R^2= .54845096 Adjusted R^2= .49532755
F(2,17)=10.324 p<.00116 Std.Error of estimate: .93646

	BETA	St.Err.of BETA	B	St. Err. of B	t(17)	p-level
Intercpt			-4.39334	1.75592	-2.50202	0.02285
MASS	0.54018	0.16298	0.04405	0.01329	3.31442	0.00410
SPEED	0.50662	0.16298	1.30246	0.41900	3.10851	0.00639

Regression Summary for Dependent Variable: %Wcon
R= .70126601 R^2= .49177402 Adjusted R^2= .46353925
F(1,18)=17.417 p<.00057 Std.Error of estimate: 3.7595

	BETA	St.Err.of BETA	B	St. Err. of B	t(18)	p-level
Intercpt			27.45343	4.229742	6.490569	4.19E-06
MASS	-0.701266	0.1680321	-0.222655	0.053351	-4.173406	0.000571

Regression Summary for Dependent Variable: %Wcon
R= .78527685 R^2= .61665973 Adjusted R^2= .57156087
F(2,17)=13.674 p<.00029 Std.Error of estimate: 3.3597

	BETA	St.Err.of BETA	B	St. Err. of B	t(17)	p-level
Intercpt			48.26693	9.618076	5.018356	0.000105
MASS	-0.448709	0.1845711	-0.142467	0.058602	-2.43109	0.026409
%STANCE	-0.434362	0.1845711	-0.353506	0.150213	-2.353361	0.0309