RELATIONSHIP BETWEEN MECHANICAL AND PHYSIOLOGICAL ENERGY COSTS AND EFFICIENCY OF TREADMILL WALKING IN ACTIVE AND INACTIVE FEMALES

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INTRODUCTION

The energy cost of walking is traditionally examined from two perspectives - biomechanical and physiological. Most researchers within these respective areas have focused on the theory and the methodology necessary to understand and measure the energy cost associated with human movement. It has been generally assumed by researchers in both areas that the energy produced by the muscles is directly proportional to the work done by the body. Exercise physiologists have focused on the metabolic cost (MC) of activity while biomechanists have attempted to measure the amount of mechanical work (MW) done by the muscles during activity. Also, of primary interest historically has been the efficiency (EFF) of human movement (i.e., MW divided by MC or the ability to convert physiological energy into MW). While much controversy remains over the methodology most appropriate for calculating MC and MW, few researchers have examined the relationship between MC and MW.

In 1981 Shorten et al. conducted a study to examine the relationship between MC and MW in four trained runners. They reported correlation coefficients between MC and MW of r=0.86 to r=0.92 for six different speeds of running. In 1987, Williams and Cavanagh examined the difference among distance running mechanics, running economy, and performance for 31 runners at a speed of 3.6 m/s. They found that running economy was related to the sum of influences of many variables rather than a single variable. Both studies examined elite runners and neither study concluded that there existed a relationship between MC and MW. This study was designed to examine a different population and activity from those in previous studies. The purpose of this study was to examine the relationship between MW and MC, MW and EFF, and MC and EFF during treadmill walking in active (ACT) and inactive (INCT) females.

METHODOLOGY

Twenty-four adult females (ages 18 to 35 years) were divided into two groups (ACT and INCT) of 12 subjects each. Each subject participated in three testing sessions. During the first testing session, anthropometric measurements were taken, and the subjects were familiarized with the treadmill and the equipment that would be used to measure oxygen uptake. A medical history questionnaire and an activity analysis form were completed by each subject. Members of both the active and inactive groups had to be free from any chronic or acute injury or physical deformity in the extremities or spinal column for the past 12 months. Subjects were classified as being either active or inactive according to their responses on the activity analysis questionnaire. The minimum criteria for inclusion in the active group was participation in any aerobic activity a minimum of 3 days per week for 30 minutes. Subjects were classified as inactive if they had participated in aerobic activity less than one time per week during the past 6 months. Individuals were also excluded if they had exercised two times per week for two consecutive weeks at any point during the past 6 months.

A maximal graded exercise test using the Modified Bruce protocol was conducted during the second session, and maximal oxygen uptake was determined. Open circuit spirometry was used to measure oxygen uptake during the third minute of each stage and during the final minute of the test. Volume of expired air was determined by a Hewlett Packard digital pneumotach. Oxygen content of expired air was measured by an Applied Electrochemistry Oxygen Analyzer, and carbon dioxide content of expired air was measured by a Beckman Medical Gas Analyzer. The third session consisted of a 10-minute walking submaximal oxygen uptake test at 0% grade. The test was conducted at a pace selected by the subject. According to Winter (1979), subjects achieve greatest efficiency when they are allowed to choose their own walking pace. Therefore, a self-selected walking pace was used to elicit the most efficient pace where the relationship between MC and MW would presumably be the greatest. Prior to the test, the subject was asked to sit quietly for 10 minutes. Resting oxygen uptake was measured during the tenth minute and was used to calculate net metabolic cost of the activity. The submaximal walking test was then administered. The subjects were allowed to adjust the pace during the first 2 minutes of the test. After that time, walking pace was maintained during the last 8 minutes at 0% grade. During the tenth minute of exercise, high speed film records were recorded at 100 fps using a Locam camera fitted with a 75 mm zoom lens. Oxygen uptake was measured using the methods and equipment described for session two. The film was digitized using a digitizer and a motion analyzer. Three-dimensional coordinates were then calculated. Segmental masses and velocities were determined, and segmental energies were calculated. MW for one stride was calculated from the instantaneous energies for each segment according to the method recommended by Williams and Cavanagh (1983). The oxygen uptake measurements were used to determine MC. EFF was determined by dividing MC into MW. Pearson correlation coefficients were calculated for MC and MW, MC and EFF, and MW and EFF for each group.

RESULTS

The active group was an average of 23.1 years of age, worked out 4.8 times per week for 47.5 min per workout, and led a moderately active lifestyle in regards to occupation. The average subject in the inactive group was 28.0 years of age, had not participated in a regular exercise program in over two years, and led a moderately active lifestyle in regards to occupation. The anthropometric profiles of the two groups were similar in all variables except percentage of body fat. The active group was 166.8 cm in height and weighed 65.0 kg with a percentage body fat of 19.8. The inactive group was 161.6 cm in height and weighed 64.8 kg with a percentage body fat of 25.6.

The active group selected a walking speed of 1.03 m/s. The inactive group selected a slower walking speed (0.95 m/s) than the active group by 0.8 m/s. Percentages of time spent in the various phases of the stride cycle were calculated and indicated a normal gait for both groups.

A physiological profile of the subjects in the active group showed they had a max VO2 of 42.6 $ml \cdot kg^{-1} \cdot min^{-1}$. Resting VO_2 was 3.0 $ml \cdot kg^{-1} \cdot min^{-1}$, or 7.1% of max VO_2. Exercise VO_2 was 9.5 $ml \cdot kg^{-1} \cdot min^{-1}$, or 22.6% of max VO_2. The inactive group exhibited a max VO_2 of 30.5 $ml \cdot kg^{-1} \cdot min^{-1}$. The resting VO_2 was 3.3 $ml \cdot kg^{-1} \cdot min^{-1}$, or 11.1% of max VO_2, and exercise VO_2 was 9.6 $ml \cdot kg^{-1} \cdot min^{-1}$, or 31.9% of max VO_2. Subjects in the inactive group had lower values for max VO_2. VO_2 was similar for both groups under conditions of rest and exercise, but VO_2 expressed as a percentage of max was higher for the inactive group during both conditions. These differences between the two groups may be attributed to the greater fitness level of the active group.

Gross and net MC were similar for both groups. Gross MC was 3.1 and 3.0 kcal/min for the active and inactive groups, respectively. The average net MC was 2.0 kcal/min for both groups. The inactive group exhibited slightly higher scores for both MW and EFF than the active group. MW was 36.1 J and 44.0 J for the active and inactive groups, respectively. The active group was only 20.7% efficient while the inactive group was 27.6% efficient.

Pearson correlation coefficients were calculated for MW and MC, MW and EFF, and MC and EFF for each group (Table 1). No significant relationship was found between MW and MC or between MC and EFF for either group. However, there was a significant correlation between MW and EFF for both the active and inactive groups.

Table 1. Correlation matrices for MW, MC, and EFF for active and inactive groups.

	MW	MC	EFF		MW	MC	EFF
MW	-	0.34	0.85*	MW	-	0.43	0.82*
MC		-	-0.27	MC		-	-0.15
EFF			-	EFF			-

*Significant at $p \leq .01$.

DISCUSSION

Researchers have identified physiological, biomechanical, and psychogenic factors that may influence the relationship between physiological energy production (MC) and mechanical work production (MW). The measure of both of these variables (MC and MW) is indirect and, therefore, requires several assumptions on the part of the investigator.

There are four physiological factors that may lead to variability in the calculation of MC and, therefore, impact the relationship between MC and MW, and MC and EFF: 1) the use of baseline subtractions; 2) the fitness level of the individual; 3) the contribution of anaerobic sources to energy production; and 4) the efficiency of the conversion of metabolic energy to mechanical energy at the level of the tendon. Exercise physiologists have debated the use of net MC vs gross MC to represent the actual physiological energy cost of a specific activity. In 1981 Stainsby et al. questioned the validity of baseline subtractions to calculate the true metabolic cost of the activity; however, in 1983 Williams and Cavanagh reported that net MC was more closely related to physiological efficiency. In the present study, net MC was used in EFF calculations to represent MC. A second factor thought to influence MC is fitness level. Previous research has produced conflicting results concerning the effects of training on economy (submaximal VO_2 per unit of body weight to perform a given task). Because the active group exhibited decreased MC for an increased workload, they appeared to be more physiologically efficient. However, these results were confounded by the decreased

MW exhibited with increased workload, possibly contributing to a lack of relationship between MC and MW, as well as MC and EFF. In 1992, Hintermeister conducted a study to examine a third factor that may contribute to a lack of relationship between MC and MW - the contribution of anaerobic sources to physiological energy production. While he found that the inclusion of anaerobic sources in estimation of MC resulted in a linear relationship between MC and MW, his findings are not considered significant to this study since slow, leisurely walking does not require anaerobic energy sources. Finally, exercise physiologists have identified the efficiency of metabolic conversion at the muscle level to be 0.2 to 0.3. This could have a direct impact on the relationship between MC and MW but at present, investigators are unable to estimate this for each individual.

Biomechanists have identified four factors that may lead to erroneous calculations of MW and have attempted to estimate the contribution of several of these factors: 1) structural differences such as location of muscle attachments, frictional characteristics of the muscle, and limitations to joint ranges of motion; 2) amount of energy transfer within and between segments; 3) positive vs negative energy changes due to muscular work; and 4) influence of elastic storage. While it is generally accepted that structural differences result in differing abilities of muscles to produce movement, investigators at the present time are unable to estimate the amount of influence that these structural differences have on MW and EFF. In 1983, Williams and Cavanagh demonstrated the variability in measures of MW when different assumptions of energy transfer were made. After review of the literature it was determined that the method recommended by Williams and Cavanagh (1983) in which transfer of energy occurred between limbs would provide the most appropriate calculations of MW for the present study. A third factor influencing the calculation of MW is the calculation of positive and negative work. Winter (1979) and Williams and Cavanagh (1983) have developed algorithms that were used in the present study to calculate the amount of negative and positive work performed during an activity. A fourth factor, stored elastic energy, has been identified by researchers as an important contributing factor in the production of MW. However, this was not considered a significant factor in slow, leisurely walking.

Psychogenic factors such as cognition (thoughts), perception (sensations), and affect (feelings) have also been identified as factors that may influence MC. This study did not attempt to control for or examine these variables, but this may be another area of research for future studies on MC, MW, and EFF.

CONCLUSIONS

There are many factors that may lead to variability or incongruencies in calculations of MC and MW, and thereby, influence the observed relationship between MC and MW. The purpose of this study was to examine a population (active and inactive females) and an activity (walking) that had not been investigated by previous researchers. Subjects were allowed to select a pace most comfortable for them where presumably the relationship between MC and MW would be greatest. Stored elastic energy and anaerobic sources of energy were not considered significant in the activity selected. Methodology was selected to minimize error in the calculation of MC and MW. However, there was no significant relationship between MC and MW for treadmill walking in active and inactive females. The significant relationship between MW and EFF may be due to more control over factors influencing the calculations of MW.

Future studies should attempt a more systematic approach to the identification of variables that may influence the relationship between MC and MW. Researchers should examine other factors such as structural differences, metabolic efficiency, and psychogenic factors that may influence the calculation of MW and MC.

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