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Metabolic Response to Repetitive Lifting Tasks: Predetermined vs. Self-Selected Pace

Trish G. Sevene[1], Mark DeBeliso[2], Chad Harris[3], Joseph M. Berning[4], Mike Climstein[5], Kent J. Adams[6]
[1,6]California State University Monterey Bay, Seaside, California, US
[2]Southern Utah University, Cedar City, Utah, US
[3]LaGrange College, LaGrange, Georgia, US
[4]New Mexico State University, Las Cruces, New Mexico, US
[5]Bond University, Faculty of Health Science and Medicine, Gold Coast, Queensland, Australia
([1]tsevene@csumb.edu, [6]kadams@csumb.edu)

Abstract- Understanding the metabolic demands of repetitive lifting tasks with different pacing strategies may help increase productivity and prevent injuries. The purpose of this study was to determine the metabolic response of repetitive lifting tasks performed with different loads and different pacing strategies. Metabolic parameters were recorded as eight male participants (age = 24 ± 6 yr, height = 173 ± 9 cm, weight = 83 ± 23 kg) participated in predetermined pace (PP) and self-selected pace (SP) weight transfer tasks. The tasks required participants to transfer two 11.4, 15.9, and 20.5 kg weight plates individually back and forth a distance of 195.6 cm horizontally and 115.6 cm vertically (lift from 40.6 cm to 156.2 cm high). Task PP required participants to transfer the 6 weight plates each minute for 10 min (i.e., 60 total transfers); task SP required participants to make the 60 transfers in 10 min or less at a self-selected pace. Statistical analyses were made using both steady state and complete task metabolic data. Results were as follows: significant ($p = 0.000$) differences were observed in VO_2 based on pacing strategy (PP or SP) during the transfer of 11.4 kg (PP = 13.0 ± 2.3 vs. SP = 17.8 ± 3.7 $ml \cdot kg^{-1} \cdot min^{-1}$), 15.9 kg (PP = 14.5 ± 2.9 vs. SP = 19.3 ± 4.9 $ml \cdot kg^{-1} \cdot min^{-1}$), and 20.5 kg weights (PP = 17.5 ± 4.2 vs. SP = 21.7 ± 5.3 $ml \cdot kg^{-1} \cdot min^{-1}$); mean VO_2 and HR were significantly ($p = 0.000$) higher during SP (19.6 ± 4.9 $ml \cdot kg^{-1} \cdot min^{-1}$, 123 ± 13 bpm) than during PP (15.0 ± 3.7 $ml \cdot kg^{-1} \cdot min^{-1}$, 109 ± 12 bpm); mean time (min) to completion was significantly faster during SP: 11.4 kg (6.5 ± 1.0), 15.9 kg (6.9 ± 1.0), and 20.5 kg (7.6 ± 1.0); regardless of pacing strategy, oxygen cost (VO_2) was significantly higher ($p < 0.05$) as weight transferred increased; and time to complete the SP transfer task increased as weight increased; also, there was no significant difference ($p < 0.05$) in total (i.e., sum of the three work bouts) energy expenditure between SP (169.0 ± 20.0 kcal) and PP (173.0 ± 17.7 kcal). In conclusion: 1) when self-selecting pace, mean VO_2 and HR were significantly higher than during predetermined pace at all workloads; 2) metabolic costs increased with increasing workload; 3) task completion was always quicker when pace was self-selected, but total energy expenditure was similar.

Keywords- *work; weight transfer; pacing.*

I. INTRODUCTION

Repetitive movement of weighted objects is the foundation of many occupations [1, 2] and injuries in the workplace are commonly associated with these lifting tasks. Work-related musculoskeletal disorders (MSDs) represent a major portion of work-related injuries and have significant economic and social costs [3, 4, 5]. Often, the same task involves a variety of lifting strategies (e.g., pacing) to ease fatigue and boredom and adapt to various constraints such as a spacing (clearance), reach, etc. [2, 5, 6]. Recognizing that MSDs occur in a complex system with many factors [6, 7, 8], it is important to isolate and analyze physiological work stress in a variety of conditions [5]. Basic research can then be applied to better analyze various tasks within work systems. Work pacing strategies are an important part of production design. Understanding the metabolic demands of repetitive lifting tasks with different pacing strategies may help prevent injury and increase productivity.

Research on pacing strategy has primarily focused on athletic competition, with an emphasis on endurance exercise [9-15]. Overall, what regulates pacing strategy remains unclear [9-15]. It has been suggested however, that strategies encompass both feedback from internal receptors (e.g., perceived exertion, muscular effort, body temperature) and external factors (e.g., work task remaining, task control, past experiences with similar tasks) [9-15]. A review of the literature revealed no studies that assessed the physiological stress of repetitive lifting tasks with different pacing strategies. However, it is reasonable to hypothesize that the same factors control the regulation of pacing during these strenuous lifting tasks as in exercise.

Physiological work stress is typically assessed as a function of metabolic response to a given work task focusing on variables such as oxygen consumption, caloric cost, and heart rate [16]. Energy expenditure or caloric cost (kcal/min) is determined from oxygen (O_2) use during an activity using the basic mathematical relationship where kcal/min equals liters (L) of O_2 use per minute multiplied by 5 kcal (kcal/min = LO_2/min x 5 kcal) [16].

Understanding the physiological demands of repetitive lifting tasks with different pacing strategies is important in job design strategies related to productivity and injury prevention. Therefore, the purpose of this study was to determine the metabolic response of repetitive lifting tasks performed with different loads (weight) and different pacing strategies.

II. METHODS

A. Subjects

Eight males (mean ± SD: age = 24 ± 6 years, height = 173 ± 9 cm, weight = 83 ± 23 kg) volunteered to participate. In the past year, all participants performed significant manual labor that included material and package handling for employment. Participants also performed aerobic and strength training for basic fitness on a regular basis (e.g., 3-4 training sessions per week at moderate to vigorous intensities). The study was approved by the University's Institutional Review Board for protection of humans prior to data collection and all participants signed an informed consent document to participate.

B. Procedure and Measurement

The repetitive lifting task was designed to mimic a production line work task performed at a large manufacturing plant. Direct observation in the plant and video tape assisted with task design. While recognizing that anatomical (e.g., height, limb length) and physiological (e.g., fitness) differences may alter stress of a given lifting task [17, 18, 19] workers often encounter lifting tasks unrelated to their size, gender or physiological readiness [17, 18, 19]. Testing took place during two sessions on different days separated by 48 hours; task assignment (i.e., PP or SP) was randomly determined. Room temperature was ~ 20° C.

After five minutes of seated rest, three randomly ordered repetitive lifting tasks took place using two 11.4 kg, 15.9 kg and 20.5 kg weight plates. Using two hands, participants transferred the individual weight plates back and forth between two weight racks as used in gym settings to hold weights. The weight racks were separated by a distance of 195.6 cm horizontally (i.e., distance apart on the floor), and 115.6 cm vertically (i.e., weight plate holders on the weight racks were set at heights of 40.6 cm [~ knee high] and 156.2 cm [~ shoulder high]). At each location, the weight plate was slid onto the weight rack and hand grip was released; then participants moved back to the original rack and transferred the second weight plate onto the rack with the other weight plate; then they reset themselves and re-grasped the weight plate to complete the next transfer back to the original rack.

With pace monitored by a technician and a metronome, task PP required participants to transfer six weights each minute for 10 minutes (i.e., 60 total transfers); task SP required participants to make the 60 transfers in 10 minutes or less at a self-selected pace. Total weight transferred during the repetitive lifting tasks using 11.4 kg weight plates = 684.0 kgs, using 15.9 kg weight plates = 954.0 kgs, and using 20.5 kg weight plates = 1230.0 kgs. Lifting technique was self-selected by participants and no foot placement instructions were given. Coupling classification did not change for any condition throughout the range of the lift (raising or lowering). A one-minute rest occurred between lifting tasks.

Metabolic parameters (O_2 consumption [VO_2 $ml \cdot kg^{-1} \cdot min^{-1}$], caloric cost [kcal], heart rate [HR]) were measured throughout the work bouts using a Parvomedics metabolic cart (Parvomedics, Sandy, Utah, USA), and a Polar heart rate monitor (Polar, Lake Success, New York, USA). The precise measurement of metabolic data this type of computerized metabolic system delivers was further enhanced by use of steady-state data from minutes 3 to 5 to compare HR and oxygen consumption during the lifting tasks [20]. Time to completion during the SP task was measured with a standard stop watch.

C. Statistical Analyses

Steady state metabolic data (O_2 consumption, caloric cost, heart rate) from minute 3 to minute 5 of each work task and condition (i.e., during the transfer of the 11.4, 15.9, and 20.5 kg weights during PP and SP) were used for analysis with ANOVA. If significant differences occurred between loads transferred, Bonferroni post hoc tests were employed to determine the location of the differences. Data encompassing the complete PP and SP work bouts were also analyzed with t-tests. Alpha level was set a priori at $p < 0.05$ for significance.

III. RESULTS AND DISCUSSION

This study determined the metabolic response (O_2 consumption, caloric cost, heart rate) of repetitive lifting tasks performed with different loads (weight) and either a predetermined (PP) or self-selected (SP) pacing strategy.

Results of the study showed statistically significant ($p = 0.000$) differences in VO_2 based on pacing strategy (PP or SP) during the transfer of 11.4 kg (PP = 13.0 ± 2.3 vs. SP = 17.8 ± 3.7 $ml \cdot kg^{-1} \cdot min^{-1}$), 15.9 kg (PP = 14.5 ± 2.9 vs. SP = 19.3 ± 4.9 $ml \cdot kg^{-1} \cdot min^{-1}$), and 20.5 kg weights (PP = 17.5 ± 4.2 vs. SP = 21.7 ± 5.3 $ml \cdot kg^{-1} \cdot min^{-1}$). The average increase in VO_2 between the PP and SP protocols was 31% or 4.6 $ml \cdot kg^{-1} \cdot min^{-1}$ (range = 24 to 37%). Mean VO_2 and HR were significantly ($p = 0.000$) higher during SP (19.6 ± 4.9 $ml \cdot kg^{-1} \cdot min^{-1}$, 123 ± 13 bpm) than during PP (15.0 ± 3.7 $ml \cdot kg^{-1} \cdot min^{-1}$, 109 ± 12 bpm). Mean time (min) to completion was significantly faster during SP: 11.4 kg (6.5 ± 1.0), 15.9 kg (6.9 ± 1.0), and 20.5 kg (7.6 ± 1.0) vs. 10 min at each work bout in PP. However, there was no significant difference ($p < 0.05$) in total energy expenditure (i.e., the sum of the three work bouts) between SP (169.0 ± 20.0 kcal) and PP (173.0 ± 17.7 kcal) (See Tables I and II).

TABLE I. OXYGEN CONSUMPTION ($ML\cdot KG^{-1}\cdot MIN^{-1}$) DURING SELF-SELECTED PACE (SP) AND PREDETERMINED PACE (PP) WEIGHT TRANSFER PROTOCOLS [MEAN (SD)].*

Pacing	Lifting Conditions		
	11.4 kg	***15.9 kg***	***20.5 kg***
SP($ml\cdot kg^{-1}\cdot min^{-1}$)	17.8 (3.7)	19.3 (4.9)	21.7 (5.3)
PP($ml\cdot kg^{-1}\cdot min^{-1}$)	13.0 (2.3)	14.5 (2.9)	17.5 (4.2)

*significant difference exists between each pacing and lifting condition

TABLE II. MEAN OXYGEN CONSUMPTION (VO_2 IN $ML\cdot KG^{-1}\cdot MIN^{-1}$), HEART RATE (HR), AND ENERGY EXPENDITURE (KCAL) DURING SELF-SELECTED PACE (SP) AND PREDETERMINED PACE (PP) WEIGHT TRANSFER PROTOCOLS [MEAN (SD)].*

	SP	PP
Mean VO_2 ($ml\cdot kg^{-1}\cdot min^{-1}$)	19.6 (4.9)	15.0 (3.7)
HR bpm	123 (13)	109 (12)
kcal	169.0 (20.0)	173.0 (17.7)

*significant difference exists between SP and PP on all parameters

To our knowledge, this is the first study to compare the metabolic cost of repetitive lifting tasks performed with two different pacing strategies. As previously stated, pacing strategy research has primarily focused on endurance (aerobic) exercise and competition [9-15], not work-related tasks; and overall, much is still unresolved in terms of specific explanations [9-15]. It has been suggested however, that strategies encompass both feedback from internal receptors (e.g., perceived exertion, muscular effort, body temperature) and external factors (e.g., work task remaining, task control, past experiences with similar tasks) [9-15].

The current study's lack of maximal cardiovascular and strength assessments makes it difficult to pinpoint the percent of maximal capacity the participants were working at during the tasks. However, when comparing the combined average O_2 cost in $ml\cdot kg^{-1}\cdot min^{-1}$ during task performance with normative percentile value data for maximal treadmill O_2 consumption [16], participants worked at 45% of maximal capacity during the SP weight transfer task and 35% of maximal capacity during PP task (i.e., the 50th percentile average maximal O_2 consumption for men age 20-29 yrs = 43.9 $ml\cdot kg^{-1}\cdot min^{-1}$). Participants worked at an average of 63% and 56% of their age-predicted maximum heart rate (eMHR = 220-age) during SP and PP respectively.

Regarding the percent of maximal strength these tasks required, lack of task specificity makes the comparisons more difficult. But, if one uses the bench press ratio (i.e., weight pushed relative to bodyweight) as a benchmark [16], the 50th percentile for 20-29 yr old men = 1.06; all participants were experienced recreational weight lifters who self-reported 1RM bench press values between 1.25 and 1.50 (~ 75 – 95 percentile of normative data) [16]; and they all routinely performed repetitive lifting tasks in their recent employment history.

Recognizing that these comparisons are not task specific, it still sheds light on the overall intensity of the present lifting tasks; and, supports that these tasks were of moderate intensity in terms of cardiovascular and muscular physiological stress.

Not surprisingly, regardless of pacing strategy (i.e., SP or PP), oxygen cost (VO_2) was significantly higher ($p < 0.05$) as weight transferred increased (mean increase = 1.5 $ml\cdot kg^{-1}\cdot min^{-1}$ between 11.4 and 15.9 kgs and 2.7 $ml\cdot kg^{-1}\cdot min^{-1}$ between 15.9 and 20.5 kgs). Increased oxygen cost may be explained by the increased recruitment of muscle mass to transfer the higher loads (i.e., the size principle of motor unit recruitment) [21]. Also as predicted, time to complete the weight transfer task during the SP trials increased significantly with each increase in load (0.41 min from 11.4 to 15.9 kgs and 0.70 min from 15.9 to 20.5 kgs). As expected due to the amount of total work performed, total caloric cost between the SP and PP tasks was similar.

In thinking about these results in relation to pacing strategy research, participants in this study were experienced with manual labor which included similar types of repetitive lifting tasks. Past experience would most likely assist with self-assessment of remaining work (i.e., a physiological "cost" projection of that work); combined with the current physiological and psychophysical feedback from the task, this may affect self-selected pacing strategy. In other words for optimal rest and recovery during repetitive lifting tasks, if the task is perceived as low physiological stress, one may choose to complete the task quickly then rest longer; in contrast to a higher intensity task where slower pacing may decrease overall fatigue more than the longer rest period achieved by completing the task quicker.

Ultimately, this decision process results in interplay between work-to-rest ratios in a self-paced repetitive lifting task similar to interval training for conditioning purposes or rest between sets in strength training; in each decision, there may be a combined assessment of personal fitness and capability vs. real and perceived workload, past experiences with similar work tasks, overall fatigue, personal control, and estimation of the amount of work remaining in the current and future tasks. Allowing freedom for workers to choose pacing strategy in a given repetitive lifting task may provide workers with valuable ability to self-regulate stress and fatigue, increase locus of control, and potentially decrease injuries related to fatigue and increase overall job satisfaction.

Limitations of this study include: 1) the lack of biomechanical analysis; however, the participants were experienced in manual material handling and utilized their own intuition and experience in completing the weight transfer tasks; 2) failure to assess the psychophysical work stress while performing the work tasks; this could have been accomplished by using the rating of perceived exertion (RPE) scale devised by Borg [22]; this is an accepted and valid subjective method of assessing perceived stress of an activity and takes into account a combination of factors such as perceived fitness, effort and fatigue levels, and environmental conditions [16]; 3) the small sample size of eight subjects which may impact the generalizability of the results; however, again, the experience of the subjects and the task specificity of the tasks increase the validity of the results.

In conclusion: 1) when self-selecting pace, VO_2 and HR were significantly higher than during predetermined pace at all workloads; 2) metabolic costs increased with increasing workload; 3) task completion was always quicker when pace was self-selected, but total energy expenditure was similar. Further research is needed to correlate predetermined and self-selected pacing strategies with cardiovascular and muscular fitness and psychophysical feedback to help determine optimal job pacing and design strategies aimed at increasing worker satisfaction and reducing work place injury.

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Trish G. Sevene, PhD is an Assistant Professor and Director of the Anatomy & Physiology Lab in the Kinesiology Department at California State University Monterey Bay, California, USA. Her research interests include the biological basis of human performance and aging, work-related lifting tasks, and masters athletes.

Mark DeBeliso, PhD is a Professor and Graduate Program Director of the Masters of Science in Sport Conditioning and Performance at Southern Utah University, USA. His research interests include mechanics and metabolics of sport movements and work tasks, strength training for all walks of life, orthopedic biomechanics, and masters athletes.

Chad Harris, PhD is a Professor and Chair of the Exercise Science Department at LaGrange College, Georgia, USA. His research interests include training effects on power production, weightlifting biomechanics, senior strength training and metabolic responses to power training.

Joseph M. Berning, PhD is an Associate Professor and Director of the Exercise Physiology Lab in the Department of Human Performance, Dance & Recreation at New Mexico State University. His research interests include strength and power training, overtraining, and warm-up strategies to enhance performance.

Mike Climstein, PhD is an Associate Professor and Program Director of Clinical Exercise Physiology and Co-Director of the Water Based Research Unit in the Faculty of Health Sciences Institute of Health and Sport at Bond University. His areas of expertise include clinical exercise physiology, sports related research and master's athletes.

Kent J. Adams, PhD is a Professor and Chair of the Kinesiology Department at California State University Monterey Bay, California, USA. His research interests include strength and power training across the lifespan, work-related lifting tasks, and masters athletes.