Relationship between energy intake and expenditure during harvesting tasks

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Abstract. The objective of this study was to compare the energy demands of manual harvesting tasks with the associated energy intake of the workers'. Fifty eight workers (29 Chainsaw Operators and 29 Stackers) were assessed in South Africa prior to, and during a 'normal' working shift. Habitual dietary analyses showed that the workers were eating less than 56% of the recommended daily allowance and were thus arriving at work with reduced energy stores. Heart rate responses were measured continuously during work and energy expenditure was predicted from the heart rate/oxygen uptake relationship obtained at a post-work progressive step up test completed by each worker. The data indicated that the tasks placed 'moderate-to-heavy' demands on the workers resulting in a significant imbalance between the energy demands of the tasks and the associated energy intake of the workers. Energy deficits were in excess of 8 000 kJ and workers lost, on average, 2.8% body mass during work while felling and cross-cutting, and 3.6% during stacking.

Keywords: Chainsaw Operators, Stackers, energy intake, energy expenditure, dehydration

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1. Introduction

An intrinsic characteristic of forestry work is that it is an activity which places undue physical demands on workers [26], and is recognized as one of the most dangerous industries in which to be employed [16]. The high injury and accident occurrence in forest harvesting has been accredited to physical fatigue resulting from difficult working postures [1], high energy-demanding tasks [16] and hostile environmental conditions including falling trees and debris [13, 25].

Despite this generally acknowledged physical overload, the energy costs of these tasks are not well established probably due to equipment and experimental constraints. Generally, harvesting tasks (felling and cross-cutting of trees and stacking of logs) are categorized as placing ‘heavy’ to ‘unduly heavy’ demands on workers contributing to early onset fatigue indicators and compromised work safety [16]. Although this is a universal problem in the forestry industry it is the author’s contention that in developing countries there are many additional compounding factors, independent of the working environment, which impact performance at work. For example Apud [2], who undertook his forestry research in Chile, argued that when conducting ergonomics research in poorer societies, consideration must be given to the workers’ nutritional status, hygiene, education and socio-economic position as these are all known to impact the capacity of the worker. In South Africa it is well known that most of the population is living in poverty with associated poor health and nutritional status [4, 9]. These and other issues such as poor education, violence and unemployment contribute to the burden that workers in South Africa and other developing countries have to deal with on a daily basis. In industrialized countries these burdens may appear irrelevant since most of the workers’ basic needs are met, while in developing countries the compounding affect of these poverty-related circumstances must ultimately have a negative impact on worker well-being and work performance. To the author’s knowledge, only one study has examined the relationship between the energy intake and energy output of manual workers in South Africa. This study, conducted by Lambert et al. [15] on sugar cane workers, found a severe mismatch between energy intake and energy expenditure. There is therefore a clear need to investigate the situation further and as such, the main purpose of this research was to determine the physical demands placed on these workers and to relate these to the associated energy intake of the workers. It was hypothesized that, because the workers are mainly rural and of poor socio-economic status, energy intake would be insufficient to meet the high-energy demands of the tasks and that this was the critical issue separating forestry ergonomics in developed and developing nations. An additional purpose was to make recommendations to the forestry industry. This had to be of minimal cost as the industry was not prepared to spend substantial amount of money.

2. Methods

2.1. Workers

Workers were recruited from the Kwambonambi harvesting area in Kwazulu-Natal, South Africa and the main ethnic group represented was Zulu. Fifty-eight forestry workers involved in the harvesting tasks of felling, cross-cutting (chainsaw operations) and stacking comprised the sample of 29 Chainsaw Operators and 29 Stackers. The protocol was approved by the Ethics Committee of Rhodes University, Grahamstown, South Africa and workers consented to participate. Basic demographic data such as age and work experience were obtained during the initial testing period. During this session, the main purpose of the study was explained in detail to the workers and supervisors with the assistance of a Zulu interpreter. Body mass of each worker was assessed using a portable Seca scale while stature was measured using a tape measure secured to a wall. Stature was measured from the floor to the vertex in the mid-sagittal plane. Body composition was assessed using the sum of seven skinfolds (biceps, triceps, subscapular, suprailiac, anterior thigh, abdominal and medial calf) and percentage body fat was estimated using the equations of Durnin and Womersley [11].

2.2. Nutritional Assessment

Habitual dietary intake was assessed using the 24-hour dietary recall method. One of the principal advantages of this method is its speed and ease of administration, and the fact that literacy of the respondent is not required, which in turn allows this method to be used across a wide range of populations [18]. The interviewer administered and filled in the responses, which only require verbal answers from the recipient. This enabled the interview to be conducted in Zulu with each interview lasting approximately 20 minutes. Additionally, the immediacy of the recall period means that respondents are usually able to recall most of their dietary intake of the previous day [24]. Thompson and Byers [24] maintain that because the recalls take place after the food has been consumed, the assessment method does not interfere with dietary behaviour.

During the interview, the Nordic Co-operation Group of specific procedures for dietary recall [7] was utilised. These include conducting the interview in a quiet, relaxed atmosphere, not giving the respondent much prior warning of the interview and using dietary aids to assist in identifying portion sizes. During the interview the workers were requested to recall all beverages and food consumed during the previous 24-hour period; this information was recorded on a data sheet broken down into seven daily intervals of pre-breakfast, breakfast, between breakfast and lunch, lunch, between lunch and dinner, dinner and after dinner. At the end of the interview, the interviewer summarized the items that had been eaten and checked with the worker that nothing had been omitted. The objective of the recall was to obtain information on the quantity and quality of the workers' current daily diet. In addition to habitual intake, energy consumption during work was also assessed by researchers who continually observed the workers and noted down everything that was consumed.

Dietary intake and nutrient composition were assessed utilizing Food Composition Tables of the Nutritional Intervention Research Unit (NIRU) of the Medical Research Council (MRC) of South Africa and the software programme *FoodFinder3* for Windows™ (Microsoft Corporation). Dietary data were entered into the programme for the assessment of nutritional intake.

2.3. Assessment of energy expenditure

Working heart rates were recorded using the Polar Accurex Plus and Polar Sports Tester heart rate monitors (Polar Electro, Finland). In the case of the chainsaw operators, the watch was secured, using adhesive tape, to the posterior deltoid to avoid interference from the chainsaw. Heart rates were assessed continuously during the work-shift. Oxygen uptake was measured using a portable metabolic system, the $k4b^2$ (Cosmed®, Rome, Italy) which has a mass of 0.8 kg and which was secured by a harness to the back of the worker. The system incorporates breath-by-breath analyses of many physiological variables although for this study, oxygen uptake and the respiratory quotient were used in the prediction of energy cost from working heart rate responses. Before each session, the $k4b^2$ was first calibrated using a Hans Rudolph 3 L syringe for volumetric calibration. The volume transducer on the $k4b^2$ was connected to the 3 L syringe and the calibration was initiated from the portable unit with six volume measurements and the average compared to the nominal value. The gas analyzers were calibrated using firstly ambient air and secondly a 16.10% O_2, 4.90% CO_2 and 79% N_2 mixture. The gas analysis tube was connected to the gas socket on the portable unit and pointed towards ambient air for the first measurement. The second measurement was performed with the gas mixture which channelled into the portable unit.

Energy cost was predicted using heart rate-oxygen uptake (VO_2) calibration curves obtained during a progressive step test completed by each worker on the completion of their shift. During this test the bench was set at a height of 350 mm. Each workload was 3 minutes in duration with step increments as follows: 82, 98, 114 and 130 steps.min^{-1}. If heart rate did not reach the highest recorded while working, an additional workload was incorporated at 146 steps.min^{-1}. Minute-to-minute heart rate was recorded using a Polar heart rate monitor and respiratory exchange measurements were collected during the test in order to calculate predicted energy expenditure from working heart rate responses on the basis of individual regression equations obtained during stepping. This technique has been validated by several authors [14, 23, 21].

2.4. *Hydration*

Total water loss was calculated by measuring changes in body mass using a portable, Seca scale. Workers were weighed in minimal clothing and any elimination was noted.

(i) Sweat loss was estimated as follows:

$$SL\ (L) = [BM\ before\ activity\ (kg) – BM\ after\ activity\ (kg)/g.ml^{-1}].$$

(ii) Relative sweat loss (SL_{REL}) was calculated by dividing absolute sweat loss by BM before the activity and multiplying by 100. Note that 1 kg is equal to 1 L:

$$SL_{REL}\ (\%BM) = [SL\ (L)/\ BM\ before\ (kg)] \times 100\ kg.L^{-1}.$$

(iii) Absolute Rate of Sweat Loss (SL_{RATE}) was estimated by dividing the absolute quantity lost by the duration of the activity (in minutes) multiplied by 60 minutes as follows:

$$SL_{RATE}\ (L.h^{-1}) = [SL\ (L)/Duration\ of\ activity\ (minutes)] \times 60\ min.h^{-1}.$$

(iv) Relative Rate of Sweat Loss ($SL_{RELRATE}$) was determined by dividing relative sweat loss by the duration of the activity and multiplying by 60 minutes as follows:

$$SL_{RELRATE}\ (\%BM.h^{-1}) = [SL_{REL}\ (\%BM)/duration\ of\ activity\ (min)] \times 60\ min.h^{-1}.$$

(v) Changes in body mass were calculated by weighing workers before the work shift and immediately on completion of their job.

2.5. Experimental procedures

The first of the two phases of the study involved obtaining demographic and anthropometeric data on the workers. The second phase, which involved the analyses of task demands in the field, were conducted during the month of December. As the work is done outdoors, the climatic conditions were an important determinant of overall physical workload. In order to minimize the effect of substantial changes in temperature, any data obtained during field investigation were discarded if the mean temperature recorded for the duration of the work shift dropped below 20 ^{0}C or increased above 30 ^{0}C. The mean ambient temperature during the investigation period was 24.3 ^{0}C while humidity levels were high (mean of 78.9 %).

Six workers were tested each day over a 2-week period. Before day break (04:00 am), when their work-shift started, these workers were taken aside and body mass (in working gear with shoes and helmets) was measured and recorded. Workers were then fitted with a polar heart rate monitor.

Workers were told that they should perform their tasks as normal and that they would be watched by a research assistant who would record any fluid or food intake; these research assistants were all either established researchers, or junior researchers reading for either an MSc or PhD at Rhodes University, South Africa and who had the relevant experience. Workers were requested to ingest fluid and food *ad libitum*. Each research assistant was responsible for observing two, and in some instances three, workers who were working in close proximity. Detailed task analyses were done in order to determine specific work procedures. In addition to continuous telemetric monitoring, heart rate was manually recorded at approximately 30 minutes intervals. Each research assistant had either a Zulu interpreter assisting, or in some instances the assistant was able to converse in Zulu. Following completion of their tasks, workers were requested to return to the outdoor ‘laboratory’ in order to be weighed and to perform the progressive step test.

3. Results

3.1. Worker profile

Similar characteristics were observed for the Chainsaw Operators and Stackers, with the exception of years of experience; the Chainsaw Operators had a mean experience of 9.5 years, whereas the Stackers had 2.9 years work experience (Table 1). All of the workers were of an ectomorphic build with a mean stature of 1714.6 mm and 1715.0 mm, and a mean body mass of 65.4 kg and 65.3 kg for the Chainsaw Operators and Stackers, respectively.

Insert Table 1 here

The habitual dietary intake of the workers is shown in Table 2. These results were compared with the mean recommended daily allowance (RDA) put forward by several authors [5, 6, 3]. According to these authors, males with a body mass of 65 kg should be consuming approximately 8 000 kJ per day; in the present investigation the Chainsaw Operators were ingesting only 49% of the RDA, while the Stackers had higher energy consumption (5346 kJ), but were still only ingesting 67% of the RDA. Protein and fat intake were marginally below the recommended level and although carbohydrate intake was sufficient for sedentary individuals, for workers involved in heavy manual labour, this is unacceptably low. The Chainsaw Operators and Stackers were only eating 110.9g and 186.8g of carbohydrate respectively per day.

Insert Table 2 here

3.2. Task Observation

With respect to the Chainsaw Operators, the overall job demands were of an intermittent nature involving the two main tasks of felling and cross-cutting, but which also required a great deal of walking from tree to tree, and periodic sitting while performing maintenance work on the chainsaw. The overall requirements of these operators, felling 280 trees and executing 2240 cross-cuts per shift, were met on a ‘work-to-task’ basis. The mean working period was 4h48min with felling constituting 31% of that total time, and cross-cutting 69% (See Fig. 1.). These workers therefore spent a considerably larger proportion of their time sawing the tree trunks into 2.5 m logs as opposed to felling them.

Insert Fig. 1. here

Once the trees had been felled, cross-cut and debarked (the latter task by a team of female workers), the Stackers collected and positioned the logs into stacks of approximately 80–100 timber lengths. On arrival at the work site, the workers cleared an area of debris and then assembled a stack frame or base on which to place the logs; this was repeated during the work shift as stack bundles are completed and new ones constructed. The workers collected logs by dragging or pulling them towards the stacking area, usually with the assistance of a ‘mechanical claw’ which helped to ‘grip’ the log (Fig. 2A.). Finally, the logs were lifted and positioned on the stack (Fig. 2B.). The methods of collecting and stacking the 2.5 m logs varied substantially and was often dependent on the experience of the worker, with the experienced workers demonstrating a more organized pattern of working. The average working time of the Stackers was 4h36 min. For both groups of workers, there were no ‘formal’ rest breaks, and by virtue of the fact that they could go home once they had completed their allotted tasks, very few workers took voluntary rest breaks. The few who did, choose to take a short rest when changing over from felling to cross-cutting.

Insert Fig. 2. here

3.3. Physiological responses

As the workers all ‘worked-to-task’, the duration of each shift varied substantially. Thus, each worker’s shift was divided into four quarters and the responses are displayed across four quarters for the two groups (Table 3).

The working heart rates of the Chainsaw Operators ranged from 85.1 $bt.min^{-1}$ to 146.3 $bt.min^{-1}$ and on average, they were working at 67% of age-predicted maximum heart rate. The Stackers worked, on average at 64% of age-predicted maximum heart rate, with responses ranging from 90.3 $bt.min^{-1}$ to 164.4 $bt.min^{-1}$, with the oxygen uptake responses followed the same trend. Kilojoule cost was higher for the Stackers across all time periods with the expenditure never dropping below 30 $kJ.min^{-1}$ (range of responses was 31.9 $kJ.min^{-1}$ to 33.8 $kJ.min^{-1}$). In contrast, the kilojoule cost of chainsaw operations was below 30 $kJ.min^{-1}$ for most of their work shift. Overall, these findings are comparable to those of Apud (1983) working with Chilean forestry workers. According to the classification of Sanders and McCormick [20], ‘moderate-to-heavy’ demands were placed on these workers.

Working heart rate, predicted oxygen uptake and energy cost remained stable during the first two quarters of the Chainsaw Operators work shift, i.e. when felling. These responses then increased significantly when the workers changed over to cross-cutting for the third and fourth quarters (Table 3, $p<0.05$). In contrast, the physiological responses of the Stackers remained constant over time. This was an interesting finding considering that the Stackers started working later than the Chainsaw Operators and were thus exposed to more heat stress later in the day and over time.

Insert Table 3 here

3.4. Relationship between energy expenditure and energy intake

With reference to the data obtained from the 24-hour dietary recall it is evident that the forestry workers participating in this project were undernourished and consequently had very limited energy stores to draw on once they were out in the field. In addition to assessing this 24-hour intake, energy intake during work was monitored and compared to the energy expenditure findings (Table 4).

Both groups of workers expended in excess of 8900 kJ during work, while energy intake during the shift was only 819.4 kJ for the Chainsaw Operators, and 143 kJ for the Stackers. Therefore, due to the present unwillingness to stop and take in any replenishment, there was a significant imbalance between the overall energy demands of the tasks and the mean energy intake of the workers. The energy deficits were 8661.8 kJ and 8804.2 kJ for the Chainsaw Operators and Stackers respectively.

Insert Table 4 here

3.5. Body mass changes

In addition to the fuel intake, workers consumed less than 500 ml of fluid during their shift which resulted in significant losses in body mass, on average they lost 1.9 kg (Chainsaw Operators) and 2.4 kg (Stackers) over the course of the work shift (Table 5). Even though the Chainsaw Operators took in less fluid, their body mass losses were not as substantial as those of the Stackers. This is probably because the Stackers worked in hotter conditions as they came into the area later in the day once the trees had already been felled. Consequently, the Stackers experienced greater sweat losses depicted in Table 5. Sweat rates were 0.17 $L.h^{-1}$ higher in the Stackers compared to the Chainsaw Operators. The Chainsaw Operators lost a mean of 2.8% body mass and the Stackers 3.6% body mass during their working shift.

Insert Table 5 here

4. Discussion

The first important finding of this study was the insufficient habitual dietary intakes of the workers with all workers eating substantially less than the recommended daily allowance. Particularly noteworthy is the fact that their carbohydrate intakes were less than 200g. In fact, this intake is not sufficient to sustain work performance for even a few hours and could contribute to low work capacity [9]. The findings emphasize the urgency of nutritional intervention for these workers, particularly with regard to carbohydrate content, as it is well known that a depletion of carbohydrate stores in the form of liver and muscle glycogen is a precursor for fatigue [12, 17].

Although these findings are extreme, they should be interpreted with caution as it is the author’s opinion that due to language and cultural barriers the workers may not have revealed all that was consumed, or underestimated portion sizes which is a typical problem with this type of recall method [24]. The workers assured the research team that they understood the principles but the trepidation about the findings illustrates the challenge of conducting research on rural, semi-educated and non-English speaking workers. However, even if these values are, for example, 20% underestimated, it still draws attention to the fact that these workers were not taking in sufficient nutrients for optimal health and well-being, let alone to sustain performance in a physically demanding job, and it is safe to assume that they were indeed not taking in sufficient energy and could be undernourished. O’Keefe et al. [19] cautioned that undernourished black South Africans have a predominance of respiratory disease which could comprise work efficiency. These authors also reported on the strong association between undernourishment and increased susceptibility to infection and mortality. It must be pointed out that these workers are paid a minimal salary and as such, cannot to afford much food particularly if they are supporting a family. Socio-economic concerns can therefore not be neglected.

The physiological responses suggest that although stacking carried a higher energy cost than chainsaw operations, during stacking a ‘steady-state’ was obtained over time which was not achieved during chainsaw operations. These responses and observations made while collecting data in the field suggest that the Stackers adjusted the intensity at which they worked so as not to over tax themselves for any length of time. In order to do this they tended to alternate between moving heavy logs and lighter logs, and between lifting onto a stack and clearing an area. This strategy of ‘self pacing’ is in keeping with the concept of ‘body wisdom’ first described by Cannon in 1922 [8], whereby individuals recognize that continuing at an intense pace for too long will be counterproductive and will result in the premature onset of fatigue. Recently, St Clair Gibson et al. [22] found that athletes participating in repeated ‘all-out’ sprint efforts automatically reduced their pace with each subsequent sprint effort despite perceiving they where still working at the same intensity. The increased responses of the Chainsaw Operators over time are likely due to the change in task from felling, to the more physically stressful cross-cutting. The energy deficits measured during work, of 8661.8 kJ and 8804.2 kJ for the Chainsaw Operators and Stackers respectively, were comparable to those found by Lambert et al. [15] who reported an energy deficit of 8846 kJ in sugar cane workers in South Africa.

Workers had high sweat rates (0.47 $L.h^{-1}$ and 0.64 $L.h^{-1}$ for the Chainsaw Operators and Stackers respectively) and consumed little fluid. The Chainsaw Operators consumed a mean of 230.0 ml during the work shift while the Stackers only consumed 143.0 ml. These workers thus loss significant amounts of weight which equated to a 2.8% loss in body mass for the Chainsaw Operators and a 3.6% loss for the Stackers. According to Cian et al. [10], both physical and cognitive performances are negatively affected by losses in body mass greater than 2.0%. The changes in body mass observed in this study therefore constitute a dangerous threat to not only working efficiency, but also life particularly as the Chainsaw Operators operate hand-held machinery. These energy and fluid imbalances is where intervention studies should concentrate especially as little can be done to change the nature of the tasks.

5. Conclusions

The findings overall indicate that factors intrinsic to the characteristics of the worker need to be given serious consideration when applying first world task-related ergonomics recommendations to third world workers as in all probability, they will not be able to maintain the same pace. This is based on the critical finding of the quantification of the fluid and energy imbalances. Considering that only limited, low-cost changes could be made to the task, the primary intervention strategy suggested to the forestry industry was to provide the workers with supplementation in the form of both fresh, cool water and something which is more solid or substantial. The impact of these changes was investigated and will be reported on in a follow up paper.

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Tables

Table 1

Characteristics of the workers investigated (Means and standard deviations)

	Chainsaw Operators (n=29)		Stackers (n=29)	
	Mean	SD	Mean	SD
Age (yr)	35.8	6.3	36.1	9.3
Work experience (yr)	9.5	7.77	2.9	5.2
Stature (mm)	1714.6	66.1	1715.0	58.8
Body mass (kg)	65.4	7.0	65.3	5.7
Body mass index (kg/m^2)	22.5	1.8	22.4	1.9
Sum of skinfolds (mm)	44.6	17.5	46.1	10.3
Body fat (%)	8.9	3.9	8.8	2.4

Table 2
Comparison between the recommended dietary intake (RDA) and actual dietary intake of the workers (Means and standard deviations)

	RDA	Chainsaw Operators	Stackers
Protein (g)	65.0	40.5 (±9.8)	56.2 (±13)
Fat (g)	30-80	26.7 (±3.5)	23.1 (±3.2)
Carbohydrate (g)	100	110.9 (±6)	186.8 (±12.2)
Total energy (kJ)	8000	3949 (±102)	5346 (± 86)

Table 3
Physiological responses during chainsaw operations and stacking for the four quarters of their work shift
(Means and standard deviations)

	Chainsaw Operators (n=29)			Stackers (n=29)		
	Heart rate ($bt.min^{-1}$)	VO_2 ($ml.kg^{-1}.min^{-1}$)	pEE ($kJ.min^{-1}$)	Heart rate ($bt.min^{-1}$)	VO_2 ($ml.kg^{-1}.min^{-1}$)	pEE ($kJ.min^{-1}$)
First quarter	120.7 (11.1)	19.9(6.5)	26.4 (8.6)	117.6 (11.4)	24.4 (6.2)	32.4 (8.6)
Second quarter	118.9 (12.5)	18.8 (6.3)	24.9 (8.2)	119.7 (15.23)	25.4 (7.4)	33.8 (10.5)
Third quarter	125.8 (12.5)*	21.8 (6.8)	28.8 (8.6)	116.9 (15.30)	24.2 (7.3)	31.9 (10.0)
Fourth quarter	127.4 (13.3)*	22.9 (7.2)	30.3 (9.4)	117.1 (12.95)	24.3 (6.0)	32.1 (8.2)
Entire shift	123.3 (10.8)	20.9 (6.7)	27.6 (8.6)	117.6 (12.95)	24.6 (6.5)	32.6 (9.1)

pVO_2: predicted oxygen uptake; pEE: predicted energy expenditure.
$* p<0.05$

Table 4

Relationship between the mean energy expenditure and energy intake of the workers (Means and standard deviations)

	Chainsaw Operators (n=29)	Stackers (n=29)
Energy cost ($kJ.shift^{-1}$)	9481.2 (±2571)	8947.2 (±2580)
Energy intake (kJ)	819.4 (±206)	143 (±98)
Energy deficit (kJ)	8661.8 (±2360)	8804.2 (±2481)

Table 5
Body mass changes, fluid intake and sweat rates during work (Means and standard deviations)

	Chainsaw Operators (n=29)	Stackers (n=29)
Pre-body mass (kg)	69.10 (±6.1)	67.47 (±3.2)
Post-body mass (kg)	67.16 (±5.8)*	65.06 (±2.9)*
Body mass loss (kg)	1.94 (±0.3)	2.41 (±0.3)
Fluid intake (ml)	230 (±180)	413 (±202)
Sweat rate ($L.h^{-1}$)	0.47 (±0.06)	0.64 (±0.08)

* $p<0.05$

Figure Captions

Fig. 1. Chainsaw Operator A: felling and B: cross-cutting.

Fig. 2. Stacker A: pulling the log with a ‘mechanical claw’ and B: lifting a log into position.

Figures

A

B

Fig. 1. Chainsaw operator A: felling and B: cross-cutting.

A B

Fig. 2. Stacker A: pulling the log with a ‘mechanical claw’ and B: lifting a log into position.