

The ergonomics of shovelling and shovel design— a review of the literature

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In spite of increased automation, there is still a need for muscular power and for manual tools in the modern consumer and industrial environment. Yet, although the concepts of human performance and ergonomic efficiency have been applied to various industrial tasks in recent years, they have been neglected in the design of many tools, especially shovels and spades. Therefore, the purpose of this review is to ascertain the extent to which, in the past, ergonomic principles have been applied to the task of shovelling and to the design of the shovel itself. Those design aspects which have been previously neglected, but could possibly lead to improved shovelling efficiency, are outlined as a guide for further research.

1. Introduction

The shovel (and spade) is a basic tool that has evolved over many centuries of use in various applications. As primitive humans turned from collecting wild edibles to growing plants, they probably started with a digging stick but later flattened it to improve performance. Sheathing in iron increased the shovel's (or spade's) durability, and eventually it became the tool as we recognize it today (Blandford 1976). Although the application of ergonomic principles to such tool design has been reviewed previously, most of these reviews have been limited to hand tools (Greenberg and Chaffin 1977, Tichauer and Gage 1977, Tichauer 1978, Konz 1974, 1979, Fraser 1980). The discussion of ergonomic principles in shovel design has been generally omitted, perhaps, because of the belief that the thousands of years of experience applied to such a common tool would have produced an implement optimally suited to human use with no room for improvement. That such an evolution did not occur is evidenced by the existence in the 1930s in Germany of over 12 000 different types of shovels with variations in style for different regions—all used for exactly the same task (Lehmann 1953). Therefore, an examination of the literature is necessary to ascertain whether ergonomic principles have indeed evolved in both the design and use of the shovel.

Spades are used to cut turf and lift and turn soil, typically in such operations as digging holes or ditches or cutting peat. Spade shafts are typically straight or slightly curved and are traditionally made of wood with a very smooth surface, so that easy gliding is provided for the hands. The total spade length is adjusted either to the elbow or to the waist (Drillis 1963). Shovels are used to lift, move and toss loose soil or grain. A shovel consists of a broad, flat blade with turned up edges, a socket and a handle. The length of the shovel is adjusted to the operator's xiphoid process of the sternum (Drillis 1963).

The front of the blade faces up, the back faces down. The upper portion of a blade, by which it is fastened to the shaft, is the socket. The socket, if stamped from a flat sheet, is generally rolled over to form a crimp known as a frog (figure 1). This frog produces a compensating hollow in the back, yielding a hollow-back socket. If the socket is filled in to prevent earth from clogging the hollow, it becomes a closed-back socket. The blade can be either a round point or a square point (figure 1).

The shaft may either taper to an end or have a handle. The handle traditionally has been of a T form, but more lately of a D form. The long spades are generally from 1.2 to 1.27 m long, while the short D handle is

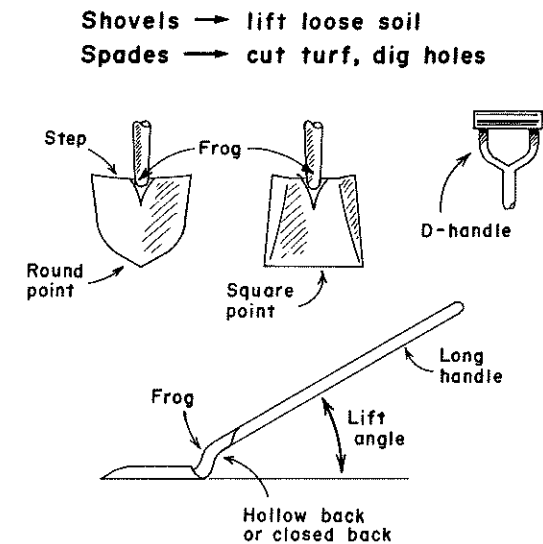


Figure 1. Common terms for shovels and spades.

about 0.7 m long. The angle of the shaft with respect to the horizontal is called the lift and provides the tool with added leverage (figure 1).

Two basic methods are presently used in manufacturing a shovel blade. The first uses a flat sheet of steel to stamp out blanks. Then, in a succession of stamping operations, the blank is pressed into the form of a shovel blade. The second method is to forge the blade from a bar. After the bar steel is displaced over dies, it is possible, through the process of rolling, to achieve thickness at points of wear and strain and thinness at points where excess weight is not desirable.

2. Laboratory and field studies

The task of shovelling was first examined scientifically by Taylor at the Bethlehem Steel Works in 1898 (Taylor 1913, Copley 1923). Taylor observed that under procedures current at the time, the loads shovelled varied from 1.6 kg for rice coal up to 17.3 kg for iron ore. By adjusting the size of the shovel to the density of the material shovelled, he found that maximum performance was attained using a load of 9.7 kg and that only 140 men were needed to complete the same work previously requiring 400–600 men.

As part of an overall report summarizing techniques to improve productivity in the construction industry, Hauer (1918) obser-

ved that a long-handled shovel increased productivity by 25% over a short-handled shovel and that shovelling performance decreased linearly by 40% for every 1 m increase in vertical throw height over 1 m. He also recommended that shovel blades have raised edges for loose material and be flat for cohering material.

Amar (1923) used more quantitative measures, such as photographs and respiration-rate recordings, to monitor the occurrence of fatigue among workers shovelling sand. By reducing unnecessary rest pauses, he increased the work output by 50%. He also estimated the gross efficiency of shovelling to be 1.8%.

Such quantitative experimentation was carried even further by Stevenson and Brown (1923) who used stroboscopic photography and respiratory gas analysis to analyse shovel types and shovelling styles in army trenching operations. They observed optimum shovelling rates of 19–21 scoops/min, a 20% decrease in shovelling performance for each 1 m increase in vertical throw height above 1.3 m and a 16% decrease in shovelling performance for each 1 m increase in horizontal throw height beyond 1.2 m. For optimum trenching, they recommended scraping the shovel along the base of the pile of material rather than thrusting directly into the pile, and using a shovel with a handle length of 0.71 m, a weight of 2.27 kg and a blade size of 0.0792 m².

The first energy expenditures of shovelling were measured by Moss (1923–24 a, b) on miners loading slack (fine remnants of screened coal). Using a Douglas bag, he found average values of 1.95 $\dot{V}O_2$ /min (Moss 1923–24 a, b) and 1.59 $\dot{V}O_2$ /min (Moss 1934).

Shovelling was next examined systematically in a series of studies done at several German work physiology institutes from the late 1920s to the 1950s. The first, by Derlitzki and Huxdorff (1927), examined the effect of shovel weight and the use of gloves in agricultural shovelling. A throw height of 1.5 m and a rate of 15 scoops/min were used. A 17% increase in shovel weight (from 2.29 to 2.68 kg) caused a 3% increase in the cost of shovelling (0.0934–0.0964 kcal/kg). The use of gloves produced an 8% increase in the cost of shovelling (0.0956–0.1044 kcal/kg) and was rationalized by the increased difficulties of holding the smooth handle with gloves.

In Wenzig's (1928, 1932) experiments, a subject shovelled leather balls filled with sand and lead shot into a box-like structure with an adjustable wall height. The shovel weighted approximately 2.5 kg, had a lift angle of 35° and had a handle length ranging from 0.48 to 0.84 m. A shovelling rate of 8 scoops/min was maintained. Energy expenditure (\dot{E}) was measured with a Douglas bag, and efficiency was calculated from external work, incorporating changes both in potential and kinetic energy.

A summary of Wenzig's data is given in table 1. As one would expect, \dot{E} increased with increasing load (0.097 kcal/kg), increasing vertical height (0.11 kcal/m), and increasing throw distance (0.14 kcal/m). The efficiency of shovelling was not as clear cut, typically having minimums in the mid-range of values. Thus, that lowest efficiency occurred at a height of 1 m was rationalized by Wenzig as the trade-off between the lower \dot{E} of the static posture at 0.5 m and the reduced amount of wasted work for larger body movements. Similarly, the lowest efficiency occurred at a 2 m throw distance and was rationalized in that, at a 1 m distance, little body movement was needed, at a 2 m distance, some movement was necessary but was not completely utilized, while at a 3 m distance, the full movement could be efficiently utilized. On the other hand, a 7.5 kg load was consistently found to be most efficient, which was a bit lower than Taylor's (1913) value of 9.7 kg.

Two shovelling postures were utilized: posture 1—the subject standing sideways at 1 m distance from the box; posture 2—the

subject standing directly next to and in front of the box, but facing away from the box and shovelling over his shoulder. In all cases, posture 2 gave lower \dot{E} than posture 1. Wenzig concluded that this was due to the large rhythmic movements needed for posture 1 as opposed to the smaller shovel flips utilized in posture 2. The data on shovel handle length indicated the 0.64 m handle to be typically most efficient for constrained postures. Consequently, Wenzig deduced that a very short handle required a larger radius of movement and, therefore, greater energy expenditure, while a longer handle required a shorter radius of movement which impeded the rhythmicity.

Simonson (1929) attempted to apply Wenzig's (1928) results to sand shovelling in a foundry casting operation. Rather than adjust floor heights to obtain an optimal throw height or to change other shovelling parameters, which would have resulted in only about a 20% saving in energy expenditure for a very small component of this particular job, Simonson recommended that the shovelling component be totally eliminated through the use of mechanical feeders.

Kommerell (1929) examined shovelling in stooped postures under simulated low-seam mining conditions. The height of the seam, the throw distance and the length of the shovel handle were varied while using a 2.5 kg shovel in three different postures. Posture 1 was identical to Wenzig's (1932) posture with the subject standing sideways and maintaining the shovel directly in line with the motion of shovelling. In posture 2, the subject also stood sideways but started with the shovel perpendicular to the line of motion. The subject then rotated both his torso and the shovel in the proper direction. Posture 3 was a variation of posture 2, with a shorter range of motion. Stroboscopic photographs were used to calculate various components of mechanical work.

The results of the study, which utilized a constant load of 9 kg, are given in table 2. For throw distances longer than 2 m, posture 2, with a slightly larger swing, gave the best performance. Lowering the working height from 1.2 to 1.0 m increased \dot{E} by about 10%. A shovel with a handle length of 0.66 m was about 10% more efficient than a longer one of 0.9 m, probably because of better manoeuvrability in the constrained working environment. The most efficient load turned out to be about 11 kg, about 20% higher than Taylor's (1913) recommended

Table 1. Net energy expenditure and efficiency of shovelling as a function of throw height, throw distance, shovel load and handle length (from Wenzig, 1928, 1932).

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Table 2. Gross energy expenditure of shovelling as a function of handle length, seam height and throw distance (from Kommerell 1929).

\dot{E} (kcal/scoop)					
Length of handle (m):		0.9		0.66	
Throw distance (m):		2.0	2.5	3.0	2.5 3.0
1.0 m seam height					
Posture					
1		0.774	0.922	1.231	—
2		0.849	0.915	1.009	0.876 0.906
3		0.770	0.908	1.099	0.882 1.005
1.2 m seam height					
Posture					
1		—	0.811	—	—
2		—	0.821	—	0.809
3		—	0.857	—	0.825

Table 3. Shovelling performance as a function of throw height, throw distance and load (from Spitzer 1950).

Shovelling performance ($\times 10^3$ kg/shift) based on $\dot{E} = 3.33$ kcal/min									
Distance (m):		1			2			3	
Throw height (m)		5 kg load	7.5 kg load	10 kg load	5 kg load	7.5 kg load	10 kg load	5 kg load	7.5 kg load 10 kg load
0.5		27	31	30	18	21	22	12	16 18
1.0		19	24	23	14	16	17	11	14 15
1.5		15	19	18	12	14	14	11	13 13
2.0		14	17	15	11	13	12	10	13 12

value. Also, since the efficiency of shovelling was highest for higher rates of shovelling, Kommerell concluded that it was best to work as quickly as possible and to have frequent rest periods.

Lehmann (1933) attached two piezoelectric strain transducers to a shovel handle and measured axial and bending stresses during shovelling. The largest compressive forces were obtained during the penetration phase while the largest tensile forces were obtained during the swing-back phase. Lehmann (1933) concluded that this was a useful method for measuring the dynamic forces and movements involved in a task.

In a set of practical experiments without the use of physiological measurements, Kirsch (1939) determined the time and number of shovelfull needed to move 1 m^3 of stone, gravel and sand under an incentive

system. The results indicated that lightweight shovels (less than 29% of shovel load) were 20% more efficient than heavier shovels at loads of 6.2 kg. With 8.4 kg loads, the difference decreased to 5%, while with 11.1 kg loads, the difference became negligible. This effect can be rationalized from the standpoint that the wasted work due to shovel weight per kilogramme of shovel load will be most noticeable with small shovel loads. Kirsch (1939) also examined the effects of blade shape on shovelling various materials and recommended shovels with a square point, flat blade and raised edges for coarse-grained materials (e.g. rocks, coal, coke, ore) and shovels with a round point, curved blade and slightly raised edges for fine-grained materials (e.g. sand, soil).

Vennwald (1939, 1940) examined various aspects of spades for their suitability in digging graves. A mechanical device was

Table 4. Recommended shovel blade sizes (from Lehmann 1953).

Material shovelled	Density (kg/m ³)	Blade size (m ²)
Iron alloys	3700	0.05
Iron ore	2500	0.07
Sand, dirt (moist)	2000	0.09
Basalt	1800	0.09
Sand, dirt (dry)	1500	0.12
Coal	800	0.18
Coke	400	0.2

constructed to press uniformly various blades into the soil, which could be varied according to consistency and moisture content. Vennewald established a resistance factor inversely proportional to the efficiency of penetration and postulated that this resistance factor was composed of frictional resistance on the flat of the blade and of end resistance due to the thickness of the cutting edge of the blade. He reduced the frictional surface resistance by constructing a pointed wedge on the tip of the blades. The wider the wedge, the wider the resulting crevasse in the soil, the less contact between the surface of the blade and the soil, and, thus, the smaller the frictional resistance. For damp soils (17–21% water content), Vennewald found the total friction to be almost entirely dependent on the frictional resistance, while for less damp soils, the effect of end resistance became greater. Surprisingly, commercial spades with similar resistances had widely different shapes and forms. The only differentiating factor seemed to be the arch of the blade, i.e. the soil pressed uniformly on the flat blade, creating a greater frictional resistance than for an arched blade. Modifying existing spades with the wedge did reduce energy expenditures by 9.5%.

Instead of calculating efficiencies without regard for fatigue, Spitzer (1950) measured shovelling performance for a constant energy expenditure of 2000 kcal per shift (table 3). Lowering throw height was the most important factor in increasing work output, up to a twofold increase for a 1.5 m lowering. The optimum shovelling load was comparable with Wenzig's (1928) value of 7.5 kg.

The results of a 2-year study by the Max Planck Institute for Work Physiology of a wide variety of industrial tasks were presented in Lehmann *et al.* (1950). Average energy expenditures observed for shovelling included 3.43 kcal/min for miners shovelling

coal and 3.17 kcal/min for construction workers shovelling gravel.

Lehmann (1953), in his well-known work physiology text, provided a very good review of the previous studies of shovelling as well as a set of recommendations for choosing the blade size, based on the density of the material being shovelled (table 4). He also presented new data on the effects of shovelling rate and load on shovelling performance (table 5). In general, for a constant \dot{E} , the faster the rate, the greater the amount of material shovelled and the less the effective work time. This corresponded with Kommerell's (1929) recommendations of faster work rates and more frequent rest pauses.

In terms of handles and grips, Lehmann (1953) recommended a length of 0.64 m for short handles with either a T or D grip. On the question of whether a long or short handle is better, he withheld judgement because of lack of concrete evidence. For spades, he recommended a flatly curved, round point but a more pointed cutting edge for extremely hard turf and the wedge modification to reduce fractional resistance (Lehmann 1934).

Dressel *et al.* (1954) examined the effect of the coarseness of the shovelled material on digging and shovelling. Under a variety of shovelling conditions, but for a constant \dot{E} , the results in table 6 were obtained. Shovelling performance decreased with the increasing coarseness of the shovelled material due to the difficulties encountered in penetrating the piled material. Thus, shovelling split brick with a grain size of 5 mm was, on the average, 17% more costly than shovelling sand, while shovelling gravel with a grain size of 7–15 mm was 21% more costly than sand, and gravel with a grain size of 15–30 mm was 37% more costly than sand. Similar to Wenzig's (1928) and Spitzer's (1950) observations, the optimum load tended to centre

Table 5. Gross efficiency and shovelling time as a function of shovelling rate and load for a constant $\dot{E} = 3.33$ kcal/min (from Lehman 1953).

Shovel load (kg)		Rate (scoops/min)											
		20			15			12			10		
		Efficiency (%)	Minutes	Efficiency (%)	Minutes	Efficiency (%)	Minutes	Efficiency (%)	Minutes	Efficiency (%)	Minutes	Efficiency (%)	Minutes
3	3.58	34.0	3.43	43.3	52.2	3.30	60.0	4.00	57.0	—	—	—	—
6	4.64	22.0	4.53	28.7	34.9	4.41	41.0	4.64	44.0	—	—	—	—
9	5.15	16.3	5.06	21.3	26.1	4.95	31.0	5.03	35.8	4.39	55.6	—	—
12	5.45	12.9	5.39	17.1	21.0	5.31	24.9	5.27	30.0	4.78	45.3	4.60	54.6
15	5.66	10.7	5.59	14.1	17.5	5.53	20.5	5.41	26.0	5.08	38.5	4.92	46.7
18	5.80	9.2	5.75	12.1	15.0	5.68	17.8	5.48	26.0	5.25	33.2	5.06	40.0

Table 6. Shovelling performance as a function of the coarseness of the shovelled material (from Dressel *et al.* 1954).

Throw height (m)	Shovelling performance ($\times 10^3$ kg/hour) based on $\dot{E} = 3.33$ kcal/min			
	Sand	Split brick (< 5 mm dia.)	Gravel (7–15 mm dia.)	Gravel (15–30 mm dia.)
0.5	4.5	3.7	3.5	3.0
1.0	3.7	3.2	3.0	2.6
1.5	3.2	2.8	2.7	2.4

around 8 kg, and similar to Lehman's (1953) results, the optimum shovelling rate approached 20 scoops/min.

Dressel *et al.* (1954) also compared two digging techniques, a horizontal penetration into the gravel pile versus a gradual scraping off of the gravel. As in the case of Stevenson and Brown (1923), the scrapeoff technique used 15–17% less energy than direct penetration for the 7–15 mm gravel and perhaps 2% less for the 15–30 mm gravel. The authors rationalized that the larger grains individually resisted penetration equally for both techniques in contrast to the general pressure exerted by the smaller grains acting together, which resisted the direct penetration more than the scrapeoff.

A later study (Müller and Karrasch 1956) used a different approach from the previous studies by examining endurance aspects and by neutralizing the empty work of the shovel weight. Thus, for larger loads, heavier shovels were used and for smaller loads, lighter shovels were used. Shovelling performance was measured by energy expenditure and recovery pulse rate, the number of pulses counted from the end of the work till the pulse rate reached resting levels. To avoid worker fatigue, the recovery pulse rate was limited to 50, and the resulting performance was termed the endurance-performance limit. Various combinations of shovel load/weight and shovelling rates (as shown in table 7) were used to achieve work intensities above and below the endurance-performance limit. The maximum endurance-performance limit (90 kgm/min) was attained at a shovel load of 5 kg with an efficiency of 5.1%.

Müller and Karrasch (1956) rationalized their results as follows: better efficiencies

were obtained at higher work rates because of the uninterrupted rhythmic motion, whereas at slower rates, added cost is incurred as the body returned to an upright posture. The lower endurance-performance limits for higher loads were due to greater static loading on shoulders and arms and the decreased circulation to the active muscles there. They recommended a lowering of the optimal shovel load from the 8 kg suggested by previous researchers (Wenzig 1928, 1932, Kommerell 1929). Whereas the other researchers had only used lowest \dot{E} or highest efficiency, Müller and Karrasch also included circulation and occlusion effects via the recovery pulse rates. Another problem in previous research had been the use of relatively heavy shovels for relatively low loads, giving rise to additional static loading. Their final recommendation was to use 5 kg loads at 18–20 scoops/min with a shovel weighing 1.5–1.8 kg.

At about this same time period, several researchers (Garry *et al.* 1955, Passmore and Durnin 1955) extensively measured the energy expenditures of coal miners performing a variety of tasks. Shovelling yielded an average \dot{E} ranging from 7.1 to 7.7 kcal/min. These values were much lower than the average value of 9.4 kcal/min found by Granati and Busca (1941) on Italian coal miners but similar to the average value of 6.9 kcal/min found later by Chakraborty *et al.* (1974) on Indian coal miners.

A more comprehensive study on shovelling performed in mines was undertaken by Humphreys *et al.* (1962). A total of 10 subjects shovelled coal from ground level onto a conveyor belt 0.23–0.30 m from the floor at a distance up to 0.91 m. Several different paces and three different postures—

Table 7. Shovelling efficiency and recovery pulse rate as a function of load (from Müller and Karrasch 1956).

Shovel load (kg)	Weight of shovel (kg)	Weight of shovel as percentage of load	Scoops/min	Lift performance (kg m/min)	\dot{E} (kcal/min)	Efficiency (%)	Recovery pulse rate
3	1.3	43.3	25	75	—	—	30
3	1.3	43.3	30	90	4.5	4.64	43
3	1.3	43.3	35	105	—	—	164
4	1.5	37.5	20	80	4.2	4.42	15
4	1.5	37.5	22.5	90	4.5	4.64	40
4	1.5	37.5	25	100	4.7	4.94	83
4	1.5	37.5	30	120	—	—	445
5	1.8	36.0	16	80	3.8	4.89	33
5	1.8	36.0	18	90	4.1	5.1	60
5	1.8	36.0	20	100	4.3	5.4	117
5	1.8	36.0	25	125	—	—	423
7	2.0	28.6	6	42	2.5	3.9	36
7	2.0	28.6	8	60	3.3	4.22	50
7	2.0	28.6	10	70	3.6	4.52	64
7	2.0	28.6	12	84	3.8	5.13	134
7	2.0	28.6	15	105	—	—	440
11	3.5	31.8	4	44	3.4	3.01	46
11	3.5	31.8	5	55	4.0	3.19	95
11	3.5	31.8	6	66	—	—	145
11	3.5	31.8	8	88	—	—	385

(i) standing, (ii) kneeling and (iii) lying on the floor—were utilized. Energy expenditure was calculated from expired air collected in a Douglas bag. Regressing energy expenditure (\dot{E}) against shovelling rate (r) yielded

$$\dot{E} = 1.34 + 0.19r \tag{1}$$

for the kneeling posture and

$$\dot{E} = 4.91 + 0.06r \tag{2}$$

for the standing posture, with typical rates of 30 scoops/min for standing and 2 scoops/min for kneeling. In the lying position, the miners expended about 1 kcal/min less for comparable rates, but also produced less coal.

In the mid 1960s, a series of laboratory studies simulating mining were performed at the Transvaal and Orange Free State Chamber of Mines in South Africa (Wyndham *et al.* 1966 a, b, 1969, Williams *et al.*, 1966), Oxygen consumption ($\dot{V}O_2$) was measured on subjects shovelling sand into a 1 ton mine car and while shovelling various grades of gravel in a variety of seam heights and slopes. In the first case, large individual variability in technique and $\dot{V}O_2$ was found. Efficiency tended to peak at high shovelling rates of 18 scoops/min, again substantiating previous findings (Lehmann 1953, Dressel *et al.* 1954, Müller and Karrasch 1956). On the other hand, the recommended 8 hour work rate of 50% $\dot{V}O_{2\text{max}}$ was later severely criticized (Minter 1968).

For the second case (results given in table 8), the reduction of seam height from 1.83 and 1.07 m down to 0.71 m greatly reduced the efficiency of shovelling and the work output due to the cramped kneeling postures. \dot{E} increased with both increasing throwing distance and worsening posture: 4.9%/m for 1.83 m seam heights, 8.2%/m for

1.07 m seam heights and 11.5%/m for 0.71 m seam heights. Changing the slope in the seam from level to 15° below horizontal increased the distance of throw and the load shovelled for a total work output increase of 23–54%. The roughness of the foot wall had no significant effect on \dot{E} because the surface gravel was compressed into a relatively firm and smooth surface. \dot{E} did increase with the increased coarseness of the shovelled material with results similar to those of Dressel *et al.* (1954).

As part of a battery of tests to simulate coal mining in a laboratory environment, Buskirk *et al.* (1972, 1975) had subjects shovel pine blocks with lead cores into a bin which returned a measured amount to be reshovelled. The shovel used had a 0.6 m handle, a 0.116 m² square flat blade and a weight of 3 kg. The results indicated that for continuous shovelling work not to exceed the recommended physical work capacity of $\frac{1}{3}\dot{V}O_{2\text{max}}$ (Lehmann 1953), a light workload would be required. This workload, corresponding to a 10 kg load lifted six times per minute for younger men and a 7 kg load lifted six times per minute for older men, is quite a bit lower than that suggested by the previous researchers. Also, kneeling postures required on the average 10% less energy expenditure than a standing posture.

Ayoub *et al.* (1981) studied miners shovelling coal and found average \dot{E} s as high as 9.3 kcal/min but with a very short average task duration of 3.8 min. Also, typically at the beginning of the task, the rate of shovelling was 25 scoops/min, but after several minutes of continuous work, the rate dropped to between 16 and 17 scoops/min.

Morrissey (1980) and Morrissey *et al.* (1983) had subjects shovel material across a 0.53 m barrier at a rate of 17 scoops/min in a

Table 8. Shovelling efficiency as a function of seam height and shovelling rate (from Wyndham *et al.* 1969).

Rate (scoops/min)	Seam height (m)					
	0.71		1.07		1.83	
	\dot{E} (kcal/min)	Efficiency (%)	\dot{E} (kcal/min)	Efficiency (%)	\dot{E} (kcal/min)	Efficiency (%)
3	6.08	2.90	5.91	4.10	7.37	4.37
4	7.12	3.15	6.79	4.21	7.99	5.05
5	7.74	3.26	7.66	4.59	9.36	5.45
6	8.41	4.15	8.7	5.82	9.43	6.36
10	9.74	4.83	9.74	6.91	11.57	7.02

variety of postures. The shovel weighted 4 kg and had a lift of 0.25 m. Similar to the findings of Buskirk *et al.* (1972, 1975), kneeling postures produced 6.4% lower \dot{E} than standing, and restrictions on posture increased \dot{E} over normal posture: a 6.5% increase for 80% of erect posture and a 13% increase for 60% of erect posture. Also, heart rate tended to be a good indicator of the strain caused by constrained posture.

A recent reference in the 1983 Ergonomics Society Lecture (Sen 1984) made reference to an earlier study (Sen and Bhattacharyya 1976) in which a second handle was added to improve shovelling operations. Unfortunately further details were not given.

3. Summary and recommendations

3.1. Optimum parameters in a shovelling task

The most important shovelling task parameters are the shovelling rate, the shovel load, the throw height, the throw distance, the posture and technique used and the properties of the shovelled material. These, in general, have been investigated very thoroughly and, therefore, fairly consistent optimum parameters can be deduced from the cited literature. The greatest discrepancies occur because of the varying criteria used to decide the optimum point, the main case being the use of pure efficiency as the criterion without regard for the total energy expenditure falling within the recommended physical work capacity of the worker.

3.1.1. *Shovelling rate.* All of the early studies (Stevenson and Brown 1923, Lehmann 1953, Dressel *et al.* 1954, Müller and Karrasch 1956, Wyndham *et al.* 1966 b) consistently agreed on a high rate of shovelling in the range of 18–21 scoops/min. Adjusted data from the two most complete studies (Lehmann 1953, Müller and Karrasch 1956) are plotted in figure 2. Although quite different in other aspects, both data sets show clearly increasing efficiency with increasing shovelling rates. The effect levels out at higher rates and with other factors such as recovery pulse rate tending to limit shovelling rates, values of 18–21 scoops/min are quite reasonable. This result can be explained primarily due to the ergonomic principle of utilizing frequent and short work–rest cycles to gain maximum benefit from exponential recovery curves. Deviations are found in Humphreys *et al.* (1962) who observed rates in miners as high as 30 scoops/min, but recommended lower rates. Wyndham *et al.* (1969), and Buskirk *et al.* (1972, 1975), utilized shovelling rates of 5–6 scoops/min, but both of these were found under constrained postures under simulated mining conditions. Therefore, the rate of 18–21 scoops/min seems to be an acceptable optimum for a shovelling rate.

3.1.2. *Shovel load.* The consensus on shovel load is not as clear as for shovelling rate. The range for an optimum load is from 5 to 11 kg, depending on the decision criterion used, on the shovelling rate used and on the weight of

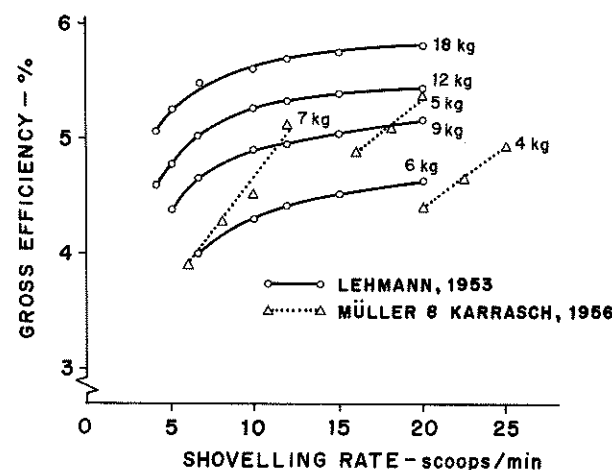


Figure 2. Efficiency of shovelling as a function of shovelling rate and load.

the shovel used (which was not always specified). Thus, based on shovelling performance, Taylor (1913) recommended a 9.7 kg load, while Stevenson and Brown (1923) cited 4.5 kg as the optimum load for a shovelling rate of 18 scoops/min. Wenzig (1928, 1932), using efficiency as the criterion, indicated 7–8 kg to be optimum for a 2 m throw height (at a rate of 8 scoops/min), with slightly lower loads for higher throws and slightly larger loads for lower throws. Kommerell (1929) indicated 11 kg for the low rate of 5–8 scoops/min. Spitzer (1950) and Dressel *et al.* (1954) recommended 8 kg for faster rates of 15–20 scoops/min. Müller and Karrasch (1956) indicated 5 kg, based on heart-rate recovery. For constrained mining conditions, Wyndham *et al.* (1969) specified 6.8 kg at 5–6 scoops/min and Buskirk *et al.* (1972, 1975) 7–10 kg at 7 scoops/min.

Adjusted data from the two most complete studies (Lehmann 1953, Müller and Karrasch 1956) are plotted in figure 2. The results are quite different. Lehmann's data indicate increasing efficiency with increasing loads. Using efficiency as the sole criterion without regarding other factors, does support the obvious conclusion that maximizing useful load with respect to the amount of wasted body weight moved is the optimum strategy. However, the increased static load gives rise to increased circulatory stress in the form of increased heart rate. Thus, Müller and Karrasch (1956) used the recovery pulse rate as a second criterion. Maximizing

efficiency given constrained recovery pulse rates yielded optimum loads between 5 and 7 kg. (The difference in slopes between the studies is the result of Müller and Karrasch (1956) equalizing shovel weight between different loads.) Thus, for high rates of shovelling (18–20 scoops/min), the lower end of the load range (5–7 kg) may be more appropriate (which follows the principle of reducing static loading on the circulatory system) while for lower rates (6–8 scoops/min), the higher end of the load range (8 kg) may be acceptable (which follows the principle of increasing efficiency with larger loads).

3.1.3. Throw height. Two conflicting decision criteria are found in the literature. Increasing the throw height, especially above 1 m, increased the efficiency of the shovelling task (Wenzig 1928, 1932, Spitzer 1950) as shown in figure 3. However, it also increased total energy expenditure. Thus, if reasonably possible considering task constraints, the throw height should be reduced, i.e. a reduction in height from 2 to 0.5 m reduced \dot{E} by 50% (Spitzer 1950). On the other hand, since the shovelling performance was reasonably constant up to a height of 1.3 m (Stevenson and Brown 1923), an acceptable throw height may be as high as 1–1.3 m.

3.1.4. Throw distance. The same conflicting criteria that applied to throw height apply also to throw distance. Wenzig (1928, 1932)

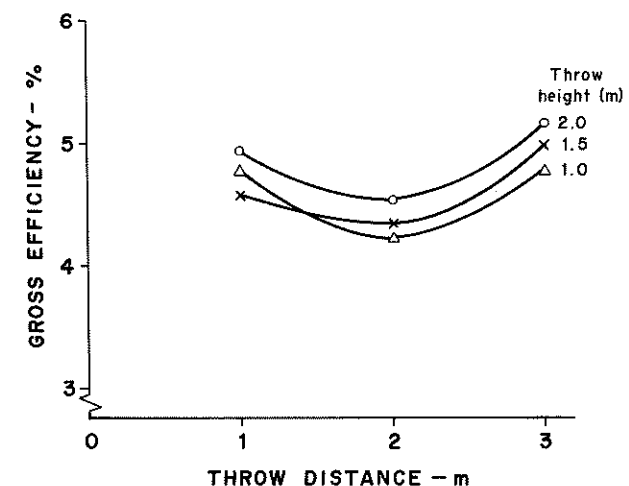


Figure 3. Efficiency of shovelling as a function of throw height and throw distance. (Composite data from Wenzig 1928, 1932 and Spitzer 1950.)

and Spitzer (1950) found minimum efficiency at a distance of 2 m with steadily increasing efficiencies thereafter as shown in figure 3. However, again energy expenditure increased correspondingly. Stevenson and Brown (1923) observed uniform shovelling performance up to a distance of 1.22 m. Since these lower distances have a lower \dot{E} and a greater efficiency than at 2 m (due to the incomplete utilization of necessary body movements), then throw distances of up to 1.2 m may be optimum.

3.1.5. Posture. Constraining the posture used in shovelling (typically by decreasing the height of the workspace as in a low-seam mine) increases the energy expended as well as decreasing the efficiency of the task. Thus, lowering the working height from 1.2 to 1.0 m increased \dot{E} by 10% (Kommerell 1929); lowering the height from 1.83 to 1.07 m reduced efficiency by 9%; lowering the height from 1.83 to 0.71 m reduced efficiency by 35% (Wyndham *et al.* 1969); and reducing the working height from erect to 60% of erect height increased \dot{E} by 13% (Morrissey *et al.* 1983). The kneeling posture typically requires from 6.5% (Morrissey *et al.* 1983) to 10% (Buskirk *et al.* 1972, 1975) less energy for the same task as a standing posture. A lying posture typically requires 1 kcal/min less than a standing posture (Humphreys *et al.* 1962).

3.1.6. Technique. The technique used in shovelling can also change the amount of energy expended. Thus, Wenzig (1932) recommended standing in front of the destination but facing away and shovelling over the shoulder, rather than standing and shovelling sideways, as the former was 18% more efficient. Dressel *et al.* (1954) found that scraping the material along the bottom of the pile to fill the shovel is 15% more efficient than digging directly into the pile.

3.1.7. Material properties. The coarser and grainer the material being shovelled, the more energy will be expended. Thus, Dressel *et al.* (1954) observed that shovelling coarse gravel required 37% more energy than sand.

3.1.8. Work prediction. Based on the composite data obtained from the above-mentioned studies, two important prediction equations can be obtained. External work (W) can be regressed on three shovelling parameters: load (L), throw height (H) and throw distance (D) to yield the following

predictive equation ($r^2 = 0.984$):

$$W(\text{kg m}) = 0.514 + 0.38L + 0.448L \times D + 0.646L \times H \quad (3)$$

Similarly energy expenditure (\dot{E}) of the shovelling task can be predicted by ($r^2 = 0.942$):

$$\dot{E}(\text{kcal/scoop}) = 0.1795 + 0.0436H \times L + 0.0169D \times L - 0.036H^2 \quad (4)$$

3.2. Optimum parameters in shovel design

There are many design features of a shovel that may affect shovelling performance: shovel weight; handle type, length and lift angle; blade size, shape and thickness; and other blade features—absence or presence of a step and a closed or solid back. Of these, only a few—weight, length, blade size, shape and thickness—have been investigated, then, generally, either with inconclusive results or without specific quantitative design recommendations.

3.2.1. Shovel weight. Of the two shovels tested, Stevenson and Brown (1923) selected the heavier one (2.27 kg) as the more efficient, though other factors influenced their choice. Kirsch (1939) found that lighter shovels were 20% more efficient than heavier shovels. Finally, Müller and Karrasch (1956) recommended a shovel weight of 1.5–1.8 kg based on an incomplete study in which shovel weight was dependent on shovel load. Obviously, reducing shovel weight should greatly increase shovelling efficiency, especially if one considers this unproductive weight to be one-third to one-half of the total shovel load (e.g. Morrissey *et al.* (1983) used a 4 kg shovel). However, a more controlled study is needed before final recommendations can be made.

3.2.2. Length of handle. There is evidence that early Flemish spades had 2.5 m handles to reduce stooping (Partridge 1973). On the other hand, Stevenson and Brown (1923) recommended an 0.71 m handle length based only on a study comparing two almost equally long shovels. Wenzig (1928) found mixed results in comparing a 0.48, a 0.64 and a 0.84 m shovel. Upon retesting, he (Wenzig 1932) observed the 0.64 m shovel to be slightly more efficient. Kommerell (1929) found a 0.66 m shovel to be 10% more efficient than a 0.9 m shovel, which was very reasonable in his constrained (1.0 and 1.2 m heights) working environment. Lehmann

(1953) agreed that short handles were more efficient in constrained environments but felt that there were insufficient data to justify a recommendation for unconstrained environments. Thus, again, further experimentation is needed.

3.2.3. Blade size, shape and thickness. Kirsch (1939) and Lehmann (1953) both agreed that blade size should depend on the density of the material being shovelled: the less dense the material the larger the blade size. Thus, based on an optimum load of about 8 kg, Lehmann (1953) outlined the approximate size of blade needed for a variety of materials (table 4). The optimum shape of the blade also depends on the material being shovelled (Kirsch 1939): for coarse-grained materials (e.g. rocks, coal, ore), a square point, flat blade with raised edges; and for fine-grained materials (e.g. sand, soil), a round point, curved blade with slightly raised edges. Blade thickness (in the range 0.5–1.0 mm) was found to be unimportant as long as the blade was properly sharpened (Vennevald 1939).

3.2.4. Second handle. There are some indications that a second handle may improve shovelling performance by reducing the amount of stooping or bending required (Sen and Bhattacharyya 1976, cited in Sen 1984, Consumer Reports 1983). However, later studies did not necessarily support this hypothesis. Freivalds (1985) found that, although predicted low-back compressive forces appeared to be reduced, the second handle tended to collide with the main handle

injuring the hand and interfering with the task.

3.3. Recommendations for future research

The parameters of the shovelling task have been investigated quite adequately and a fair amount of quantitative data are available to design the task properly. The parameters of shovel design, however, have not been studied to the same degree. The data that are available for shovel weight and handle length are quite incomplete and contradictory. Thus, confident recommendations cannot be made. Parameters such as the lift angle, which could reasonably be expected to affect the mechanical stress, especially of the low back of the user, have not been examined at all. Similarly, different construction techniques, resulting in either a solid back, which adds weight to the shovel, or a hollow back, which is lighter but may clog with dirt, may affect the efficiency of shovelling. Similarly, the useful feature of a step adds weight to a shovel, yet may be justified under certain conditions. Spades, which are used for digging and typically have different blade shapes, have been completely neglected. Thus, much research is still needed before the common shovel (and spade) can be truly classified as an ergonomically designed tool.

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