ERGONOMICS, 1986, VOL. 29, NO. 1, 19–30

The ergonomics of shovelling and shovel design—an experimental study

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Keywords: Ergonomics; Shovelling; Equipment design; Efficiency, Energy expenditure.

In spite of increased automation, there is still a need for ergonomically designed manual tools in the modern consumer and industrial environment. For example, many studies have examined the work physiology involved in shovelling, but few have referred to the shovel-design parameters needed to make the task more efficient. To this end, a two-phase experimental study examined the effects of the following parameters: lift angle, the size and shape of the blade, the hollow- and the closed-back design, the handle length on shovelling performance, the energy expenditure, the predicted low-back compressive forces and the subjective ratings of perceived exertion. The results indicated the following recommendations in shovel design: a lift angle of approximately 32°, a large, square-point blade for shovelling, a round-point blade for digging, a hollow-back construction to reduce weight, a solid socket for strength in heavy duty uses, a step for digging in hard soil and a long tapered handle.

1. Introduction

Although the task of shovelling was first examined scientifically as early as 1898 (Taylor 1913) and was followed by many laboratory and field studies (reviewed in Freivalds (1985)), most of these studies examined the efficiency of shovelling as a function of the rate of the shovelling, of the load handled, of the posture used and of the throw height and distance rather than as a function of shovel design. Only a few of the very meticulous German studies looked at such shovel parameters as handle length (Wenzig 1928, 1932, Kommerell 1929) and shovel weight (Kirsch 1939, Müller and Karrasch 1956). More specific details that could be of interest in the design of shovels and spades, but that have not been examined, include such factors as: the lift angle, the size and shape of the blade, the hollow-back versus the closed-back blade and the step design. These could reasonably be expected to alter the mechanical stress on the human operator and the efficiency of task performance.

Thus, the purpose of this experimental study was to examine the effects of the above-mentioned shovel-design parameters. Phase I examined the effects of lift angle on shovelling performance, using a specially constructed shovel. Phase II examined shovelling performance, using a variety of common garden shovels.

2. Phase I—variable lift angle

2.1. *Subjects*

Seven subjects, six males and one female, were utilized in phase I. They were all students who volunteered for the study and were paid appropriately for their work. All had had some experience in shovelling, most commonly in gardening, and were screened by a questionnaire for back and hernia problems. Further information on subjects A–G is given in the table.

Subject data.

Subject	Gender	Age	Height (m)	Weight (kg)
A	M	25	1·75	73·5
B	F	22	1·73	76·4
C	M	21	1·73	75·3
D	M	21	1·68	65·8
E	M	22	1·88	77·1
F	M	22	1·85	74·8
G	M	31	1·77	64·0

2.2. *Experimental design*

An experimental shovel with an adjustable lift was constructed from a commercial garden shovel. The shovel was cut into two pieces at the socket. A joint was constructed and then welded to each of the two pieces. After the two components of the joint had been appropriately pinned, an adjustable lift of 16° intervals was created. Four angles—0, 16, 32 and 48°—were utilized.

Two different shovelling tasks were performed. Task 1 (throwing) consisted of scooping sand from the floor level and throwing it into a barrel 0·7 m high and at a distance of 1·4 m. For task 2 (digging), the subjects stood on a flattened sand pile 0·5 m deep, dug into the sand, lifted the shovelful slightly and turned the sand back into the hole as if cultivating a garden plot. The two tasks were performed in a foundry, using foundry casting sand moistened regularly to hold its moisture content within the range 2·5–4·0%.

Each subject's experimental session consisted of two repetitions of one task for four different lift angles with the experimental shovel. Five minutes of work were followed by 5 min of rest. The first 3 min of work were used as a warm-up to reach steady state, while the last 2 min were used for data. The order of the eight trials was blocked for fatigue and the values for the two repetitions averaged. The total session lasted approximately 2 hours. In all cases, the rate of shovelling was kept constant by a metronome at 18 scoops/min based on recommendations in Freivalds (1985).

2.3. *Measurements*

Four objective measures of human performance were calculated. Energy expenditure ($\dot{E}$) was calculated via a respiratory gas analysis of the expired air, using the Weir (1949) equation and data collected with the MM1 Metabolic Monitor (a system composed of a Fleisch pneumo-tachograph, a Beckman 755 paramagnetic oxygen analyser, and a Beckman 864 infrared carbon dioxide analyser). Low-back compressive forces (F_{comp}) imposed on the subject during shovelling were calculated using the University of Michigan 3-Dimensional Biomechanical Strength Prediction Model (Chaffin and Baker 1970). Calculations were based on angles measured from photographs taken of subjects in critical postures assumed during the task in a manner similar to the procedures used to validate the model (Freivalds 1982). Subjective ratings of the perceived exertion (RPE) of the shoulders/arms, of the low back and of the shovel being used were recorded during the shovelling task. This rating, developed by Borg (1973) is a scale from 6 (very, very light) to 20 (very, very hard), which has been used successfully to evaluate discomfort in the body (Corlett and Bishop 1976). Shovelling performance was calculated from the amount of sand placed in the barrel per unit time (i.e. kilogrammes per minute). For task 1 energy expenditure was normalized to body weight and to shovelling performance in order to obtain a normalized energy cost. This followed the procedure of Müller and Karrasch (1956) and allowed one to minimize the effects both of body size and of individual variation in performance of the task. For task 2 this was not possible since there was no easy way to measure the amount of sand turned.

2.4. *Results*

The analysis of variance (ANOVA) of energy cost yielded significant ($p<0{\cdot}1$) results for lift angle on task 1. Further analysis by contrasts indicated that lift angles of 0 and 48° were significantly less efficient than angles of 16 and 32° (figure 1). The ANOVA for F_{comp} also indicated a significant ($p<0{\cdot}1$) effect due to lift angle, with the F_{comp} for 0° being highest, followed by 16 and 32° and, finally, 48°, the lowest (figure 2).

The ANOVA of RPEs for low back and shovel for both tasks were significant ($p<0{\cdot}1$), with lift angles of 16 and 32° preferred over 0 and 48°.

3. Phase II—various shovel types

3.1. *Experimental design*

Four of the six garden shovels shown in figure 3 were utilized in task 1. Shovel BR is a round point, dirt shovel with a short D handle. Shovel BLR is a round point, dirt shovel with a long handle. Shovel BLS is a square point, dirt shovel with a long handle. Shovel IB2 is an irrigation shovel with a long handle and a low lift. Shovel BLS was omitted for task 2 because the square-point blade was inappropriate for digging. Shovel BLRT was added because of its light weight (a result of its hollow-back construction). A sketch of each of the shovels and further details on weight and lift angle are given in figure 3.

As in phase I, each experimental session consisted of two repetitions of the tasks for each of the four different shovels. Order was again blocked and the two repetitions averaged. The shovelling rate was 18 scoops/min.

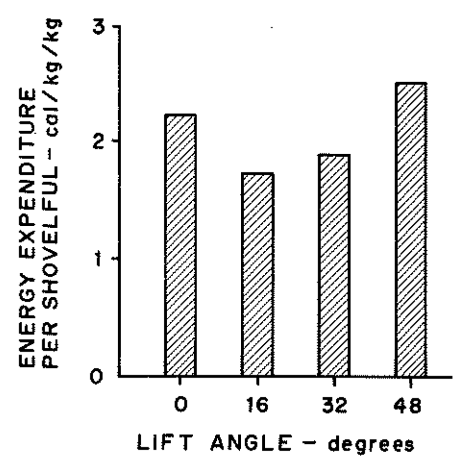


Figure 1. Normalized energy cost of a throwing task as a function of lift angle.

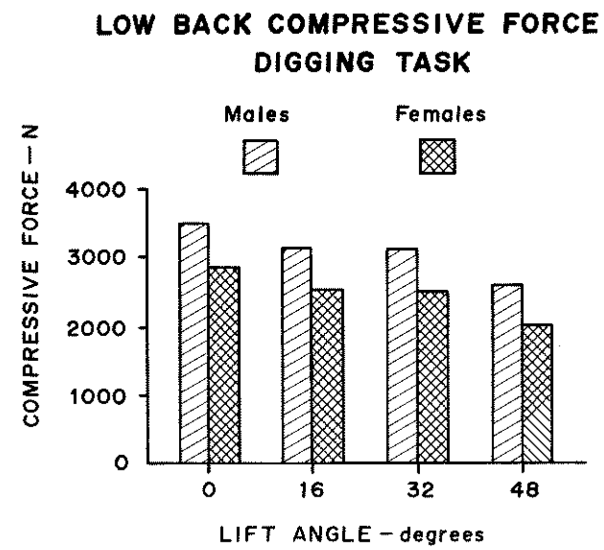
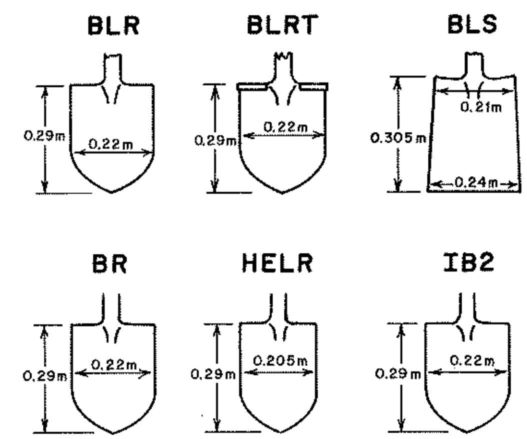


Figure 2. Predicted low-back compressive forces for task 2 (digging) as a function of lift angle.



Code	Back	Handle	Point	Weight (kg)	Lift (deg.)
BLR	Solid	Long	Round	1·93	37
BLRT	Solid, step	Long	Round	2·25	37
BLS	Solid	Long	Square	2·21	37
BR	Solid	Short, D	Round	1·74	42
HELR	Hollow	Long	Round	1·88	36
IB2	Solid	Long	Round	1·93	25

Figure 3. Physical characteristics of six common garden shovels.

3.2. *Results*

The ANOVA of the energy cost yielded significant ($p<0{\cdot}1$) results showing increasing efficiency for BR, IB2, BLR, to the most efficient BLS (figure 4). The ANOVA on RPEs for task 1 for shovels was significant at $p<0{\cdot}1$, with BR clearly disliked. The ANOVA on RPEs for the low back was also significant at $p<0{\cdot}1$, with BR again being most disliked. The ANOVA for RPEs for shoulders/arms was not significant but, again, shovel BR received the highest values for the effort required (figure 5).

The ANOVAs of all three RPEs indicated the following order of preference for task 2: BR least, IB2, BLRT, BLR and HELR most preferred (figure 6). Similar to task 1, shovel BR was universally ranked lowest for every dependent measure used. F_{comp} did not show significant shovel effects.

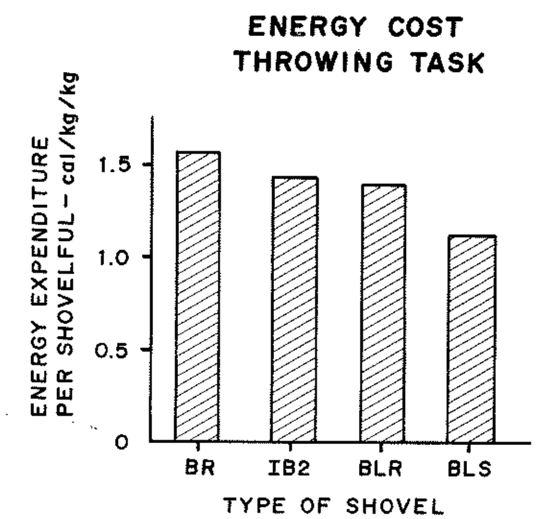


Figure 4. Normalized energy cost of a throwing task as a function of shovel type.

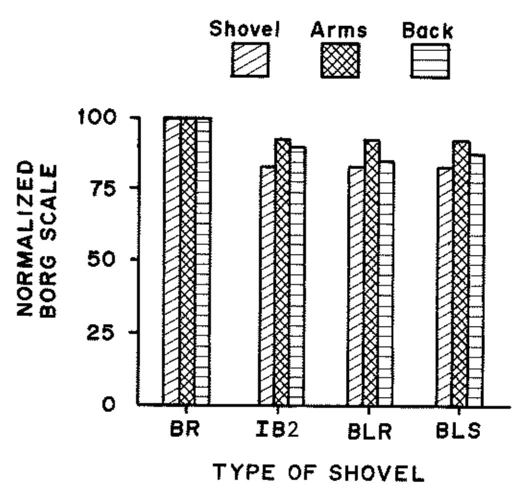


Figure 5. Normalized ratings of perceived exertion for task 1 (throwing) as a function of type shovel.

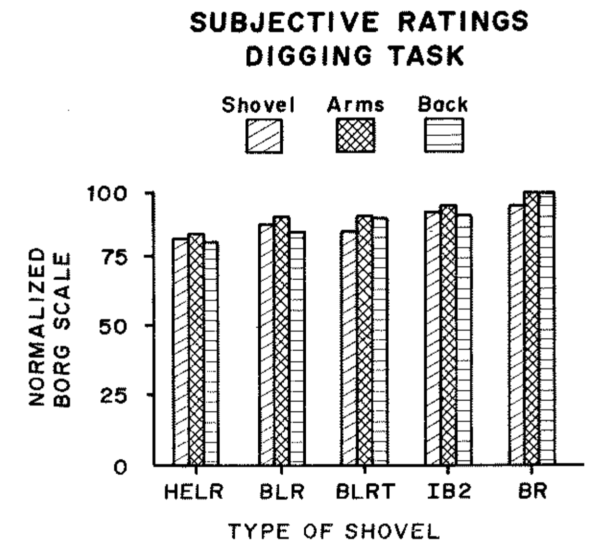


Figure 6. Normalized ratings of perceived exertion for task 2 (digging) as a function of type of shovel.

4. Discussion

4.1. *Lift angle*

Use of the normalized energy cost served as a good discriminator in identifying the effects of lift angle on shovelling performance. For task 1, lifting and throwing, the energy cost for both extreme lift angles, 0 and 48°, was significantly greater than for 16 and 32°. For 0° this was expected, since extreme bending of the torso or stooping of the whole body was required to scoop and lift the sand effectively. For 48° this was not expected, considering the negligible amount of bending required to scoop the sand. Closer scrutiny of photographs (which was also verified by the subjects) showed a sizeable portion of the scooped sand being lost from the tilted blade during the throwing phase. With energy expenditure being normalized to the amount of sand shovelled, this loss became critical to the efficiency of the shovelling task.

For task 2, digging and turning the sand, the normalized $\dot{E}$ could not be calculated since there was no easy measure of external work for merely turning the soil. $\dot{E}$, by itself, was not a good discriminator for task 2 (or for task 1) because of the large intersubject variabilities in task performance. Therefore, normalization to task performance was crucial, but, unfortunately, could not be done for task 2.

Low-back compressive forces (F_{comp}) tended to increase linearly from a low value at a 48° lift angle to a high value at a 0° lift angle. This would be the expected effect considering the fairly upright postures used with the 48° lift angle and the fairly stooped postures used for the 0° lift angle. Plotting F_{comp} versus lift angle yields the graph in figure 7. Regression of F_{comp} versus lift angle for task 1 yields a significant ($p<0{\cdot}05$) relationship:

$$F_{comp}\,(\mathrm{N}) = 4102 - 7{\cdot}74 \times \text{lift angle} \qquad (1)$$

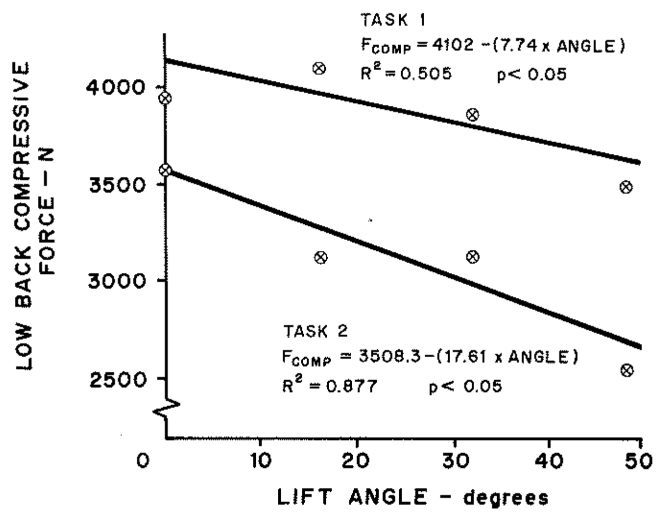


Figure 7. Predicted low-back compressive forces as a function of lift angle.

The values tended to be lower for task 2, as would be expected in view of the fact that the subject need not stoop as low to simply turn the soil as opposed to scooping a full shovelful. Again a significant ($p<0{\cdot}05$) repression is obtained:

$$F_{comp}\,(\mathrm{N}) = 3508 - 17{\cdot}61 \times \text{lift angle} \tag{2}$$

The highest values obtained during shovelling, about 4000 N, occurred at a 0° lift angle with a shovel load of 9 kg (including the weight of the shovel). Typically, the loads (including shovel weight) weighed between 5 and 7 kg and thus would give even lower F_{comp}. However, the discs and vertebrae could be damaged even from these loads. Axial compression tests on cadaver vertebral columns have shown average fracture levels ranging from 6750 N (under 40 years of age) to 3000 N (over 60 years of age), with considerable variability in each age group and with females having about 17% less compression tolerance (Sonoda 1962). Similarly National Institute of Occupational Safety and Health (NIOSH) guidelines have indicated 3400 N as an action limit for which some type of administrative controls are required (NIOSH 1981). Thus, for certain people, the shovelling task under low-lift conditions and large loads could prove to be stressful.

The RPE for all three variables—shoulders/arms, low back and shovel—tended to show significant results only when normalized to that subject's highest rating. In this manner some of the inter- and intrasubject variability could be reduced. In terms of shoulder/arm exertion, the subjects rated the 48° lift angle significantly worse than the 0, 16 or 32° lift angles for task 1. Their primary complaint was that, with the large lift angle, the load was more difficult to control during the throwing phase in task 1. During this phase, the sand tended to slide off backwards, especially with the steep left angle. In order to reduce this loss, the subjects would either slow down the motion to reduce the momentum or use an unnatural motion to maintain a more horizontal blade position. Similarly during the turning phase, the centre of gravity of the 48° lift angle blade created a larger moment arm in relation to the axis of rotation in the handle than did smaller lift angles. This required a greater torque to maintain control of the blade as it was rotated to release the sand.

In terms of low-back exertion, the subjects rated the 0° lift angle significantly worse than the 16, 32 or 48° lift angles. This is quite consistent with the results of the biomechanical predictions of low-back compressive forces which indicated F_{comp} to be highest at a 0° lift angle. Typically, the ratings were not as discriminating as the F_{comp} predictions, probably because the subjects tended to rate a lift angle worse only when it was noticeably different from the other lift angles. Thus, for the 16, 32 and 48° lift angles, the change in stooped posture was not as noticeable as for the extreme case, the 0° lift angle.

In terms of the overall exertion required to use a shovel with a given lift angle, the subjects rated the intermediate lift angles of 16 and 32° as best for task 1. This is consistent with the normalized energy cost and is probably reflected in the subjects' perception of work or fatigue.

The effects of lift angle on the various measurements were less clear for task 2, primarily because of the soft foundry sand.

4.2. *Types of shovels*

In general, the various measurements did not statistically discriminate shovel type as well as they discriminated lift angle. This was most likely due to fewer extreme differences between shovel types in contrast to the large disparity in lift angles.

Normalized energy cost statistically discriminated between shovel types. There was a clear pattern of increasing efficiency for BR to IB2 to BLR and to BLS, with a significant difference between the two extremes, BR and BLS, for task 1. This pattern can be rationalized according to the characteristics of these shovels. BR is a short-handled shovel, while IB2, BLR and BLS are long handled. The short handle required additional stooping (as can be observed in the photographs) with increased $\dot{E}$ for the same external work. The long-handled shovels eliminated this stooped posture, reducing $\dot{E}$. IB2 has a lift angle of 25° while the others have lift angles of 37°. Thus, they all fit within the middle range of lift angles tested and would not be expected to show significant differences in terms of normalized $\dot{E}$. On the other hand, BR, IB2 and BLR all have round points, while BLS has a square point, which increases the blade area. In fact, the blade area increased from 0·0604 m^2 for BR and BLR to 0·1065 m^2 for BLS, a 76% increase. Examining the loads shovelled showed a correspondingly significant but smaller (28%) increase from 3·48 to 4·31 kg.

F_{comp} did not show significant effects as a function of shovel type, although the F_{comp} per unit load was highest for IB2 and BR, the low lift and the short-handled shovel, respectively. This was expected from the more pronounced stoop posture used with these shovels.

Based on the subjective RPE, the subjects indicated a clear dislike for the short-handled shovel, BR, especially in regard to the excess stooping or bending involved with the short handle. The RPEs for BLR, BLS and IB2 were generally quite similar.

Task 2 utilized a second selection of shovels having features that might influence the digging task. The RPEs and comments given by the subjects were quite instructuve. In increasing order of preference were BR, IB2, BLRT, BR and HELR. Shovel BR was again rated worst on all three aspects due to its short handle requiring a stooped posture. Shovel IB2 was next lowest, probably because of its low lift. The next three shovels progressed according to increased lightness, BLRT at 2·25 kg, BLR at 1·93 kg and HELR at 1·88 kg. Shovel HELR was rated best in all three aspects (shoulder/arms, shovel were reasonable only within his very constrained working environment (1·0–1·2 m working heights).

In the present study, shovel BR, with a 0·71 m long handle, was consistently worse on all evaluations compared with a 1·22 m handle. Normalized energy cost was significantly higher than for all other shovels. Low-back compressive forces were higher than for most other shovels. For all three subjective ratings of perceived exertion (shoulder and arms, low back, overall shovel), BR was always rated worst. Thus, for general shovelling in an unconstrained environment, a short handle cannot be recommended.

The hollow-back construction did not lead to problems of dirt clogging the hollow, probably because of the sandy nature of the material used. In fact, the reduced weight of shovel HELR gave it the best rank among the shovels used in digging. However, more claylike material would reduce this benefit, and, as was discussed previously, the reduced scooping capacity of the blade would result in lower efficiency.

An increase in blade size from the 0·0604 m^2 round-point area of shovel BLR to the 0·1065 m^2 square-point area of shovel BLS significantly increased the amount of material shovelled from an average of 3·48 to 4·31 kg. Although this increase in load increased energy expenditure, the change is less than proportional, giving an increased efficiency for the larger load. On the other hand, this increases energy expenditure can accelerate fatigue and, therefore, some compensating factor is needed. One such factor could be shovel weight.

The shovel parameter most likely to effect a significant improvement in shovelling efficiency appears to be the weight of the shovel. Although this aspect was not thoroughly investigated in the present experiment, there are strong indications of promising results. When the weight of the shovel is approximately one-third of the load handled by the subject, a large amount of energy is wasted. This was suggested by Kirsch (1939), who found shovels weighing less than 29% of shovel load to be, on the average, 20% more efficient than shovels weighing more than 29% of shovel load, and by Müller and Karrasch (1956), who adjusted shovel weights as a constant proportion of shovel loads and recommended a shovel weight of 1·5–1·8 kg. The present study also suggested this when comparing BLRT (2·25 kg), BLR (1·93 kg) and HELR (1·88 kg) on the digging task. The subjects gave higher ratings with decreasing shovel weight.

5.2. *Summary*

Based on previous studies found in the literature and present experimental results, it is recommended that the following parameters be used in the design of the common, all purpose shovel:

(1) A lift angle of approximately 32°.
(2) A long handle.
(3) A large square-point blade for shovelling.
(4) A round-point blade for digging.
(5) Hollow-back construction to reduce weight.
(6) As light a weight as possible without sacrificing too much strength and durability.

Acknowledgments

The author would like to express his thanks to the True Temper Division of Allegheny International Hardware Group for supplying sample shovels and for

low back, shovel). Its lightness is due to its hollow-back construction which requires less steel.

An interesting question arises about trade-offs for hollow-back versus closed-back construction. The disadvantage of the hollow-back construction, aside from the weaker blade, is the tendency of the hollow to clog with dirt, making the shovel heavy and throwing it out of balance. However, the weight gained in clogged dirt will be no more, and probably less, than the weight of a forged-steel solid back. In the second case, there are no savings in energy expenditure, whereas in the first case there might be energy expenditure savings should the hollow not be clogged. In the present study, the foundry sand did not clog the hollow, and further experimental evidence cannot be provided.

Another consideration with the hollow back is that the resultant frog on the front of the blade reduces the capacity of the blade. This could be a problem, because (as was observed with the square point, BLS) a significant increase in efficiency is obtained with the larger-area blade.

One remaining aspect that was not formally described earlier in the paper was the addition of a second handle near the socket to facilitate lifting and to reduce stooping. Contrary to the findings of Sen and Bhattacharyya (1976) cited in Sen (1984), the handle, as it was designed, seemed to hinder more than help. The shovel was more difficult to use and larger torques (due to added weight) were required to rotate the blade in order to deposit the sand. Furthermore, on fast throwing movements, the hand on the pivoting handle tended to hit the main handle, interfering with the task. So, in all, the second handle was not a successful innovation.

5. Recommendations and summary

5.1. *Discussion of recommendations*

The recommendations for the various shovel parameters, i.e. lift angle, handle length, size of blade, hollow-back versus closed-back blades, step feature and weight of the shovel, will be based on both the results of the experimental study and the results from previous studies in the literature (Freivalds 1985).

Lift angle had never been examined before and was, therefore, a very important aspect of this study. Of the four lift angles examined (0, 16, 32 and 48°), 16 and 32° were consistently more efficient than 0 and 48°. This was shown to be the case for normalized energy cost and for ratings of perceived exertion. Although model predictions suggest larger lift angles to reduce low-back stresses, the extreme angle of 48° creates larger torques and reduces control during the release of scooped material. This increases energy expenditure, reduces the efficiency of shovelling and excludes the 48° lift angle from further consideration. Most of the shovels tested have approximately a 37° lift angle and, therefore, fit within the optimum range and are quite adequate. However, shovel BR has a lift of 42° which approaches the 48° extreme and thus becomes less efficient. In fact, BR was consistently rated lowest on every dependent measurement (although much of that was due to the short handle).

Handle length, another important aspect, had been examined in previous studies (Wenzig 1928, 1932, Kommerell 1929) but the resulting interpretations were contradictory. Wenzig (1928) originally found mixed results but later (Wenzig 1932) indicated the superiority of the 0·64 m shovel over the 0·84 m shovel. This result is surprising, until one realizes that Wenzig used a D handle on all three shovels, fixing the subject's hand on the handle. With long handles, this would result in a very awkward posture. Kommerell's (1929) results of a 0·66 m shovel being 10% better than a 0·90 m

providing support for this project and to Dr Don B. Chaffin, for permitting access to the University of Michigan 3-Dimensional Biomechanical Strength Prediction Model.

Malgré les progrès de l'automatisation, on a toujours besoin, dans les milieux industriels, d'outils de conception ergonomique. Par exemple, il existe de nombreuses études de physiologie appliquée au travail de pelletage, mais peu se sont intéressées aux paramètres de conception de la pelle qui rendraient le travail plus efficient. La présente étude avait pour objectif d'examiner les effets des paramètres suivants sur les performances: l'angle d'élévation, la dimension et la forme du fer, le modèle à dos creux ou fermé, la longueur du manche. On a également étudié la dépense d'énergie, les forces de compression lombaire prédites, ainsi que l'évaluation subjective de l'effort perçu. A partir des résultats trouvés, on peut proposer les recommandations suivantes: un angle d'élévation d'environ 32°, un fer de grande taille à angles carrés pour le pelletage et à angles arrondis pour le bêchage, un modèle à dos creux pour réduire le poids, un joint de prise solide pour le cas de travail ardu, un appui-pied pour le bêchage en sol dur et un manche long fuselé.

Trotz der gestiegenen Automatisierung ist in der modernen Verbraucher- und Industriewelt noch ein Bedarf an ergonomisch gestalteten Handgeräten. Viele Studien haben zum Beispiel die physiologische Arbeit verbunden mit dem Schaufeln untersucht, aber wenige bezogen sich auf die Kenngrößen der Schaufelgestaltung, die notwendig sind, um die Aufgabe wirkungsvoll auszuführen. Zu diesem Zwecke untersuchte eine zweistufige Experimentalstudie die Einflüsse der folgenden Parameter: Anhebewinkel, die Größe und Form des Schaufelblattes, die ausgesparte und die durchgehend gestaltete Rückseite, die Stiellänge bei der Durchführung des Schaufelns, den Energieaufwand, die voraussichtlichen Druckkräfte im unteren Rückenbereich und die subjektive Bewertung der erfaßten Anwendung. Die Ergebnisse geben die folgenden Empfehlungen bezüglich der Schaufelgestaltung an: ein Anhebewinkel von ungefähr 32 Grad, ein großes, quadratisch geformtes Blatt zum Schaufeln, ein rundgeformtes Blatt zum Graben, eine ausgesparte Gestaltung der Rückseite, um Gewicht zu reduzieren, einen stabilen Rohransatz wegen der Kraft bei schweren Anwendungsaufgaben, einen Tritt für das Graben in hartem Boden und einen langen konischen Stiel.

自動化が進む中にも，現代の消費者あるいは産業環境においては今もなお人間工学的に設計された手工具の必要性は存在する。例えば，シャベル作業における労働生理学的研究は多くなされてきたが，作業をさらに効率良く行うために必要なシャベルの設計パラメータについてはほとんど言及されないできた。このために，以下に示すパラメータがシャベル作業に及ぼす影響を調べるために２つの実験的研究を行った。各パラメータは，持上げ角度，シャベルの刃の大きさと形状，ホローバックとクローズドバックの形状，取手の長さであり，さらにエネルギー消費，腰部圧縮力の予測値，そして主観的努力の評定値も調べた。実験結果よりシャベルの設計において次の様な事が推奨された。特上げ角は約32°，シャベル作業には大きく先端の角ばった刃，掘り作業には先端が丸い刃，重量を減らすにはホローバック構造，条件の激しいところでの使用のためには固い軸受け，そして長い先細の取手等が推奨される。

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Manuscript received 24 July 1984.
Revised manuscript received and accepted 17 June 1985.