

Modeling costs of exposure assessment methods in industrial environments

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Abstract. Documentation of posture measurement cost is rare and cost models that do exist are generally naïve. This paper provides a comprehensive cost model for ergonomic research, documents the monetary costs of three exposure assessment methods (inclinometry, video observation, and self-report), and discusses cost components. Trunk and shoulder posture were assessed for 27 aircraft baggage handlers for 3 full shifts each using three methods typical to ergonomics: self-report via questionnaire, observation via video film, and full-shift inclinometer registration. The model accounted for costs related to meetings to plan the study, administration, recruitment, equipment, training of data collectors, travel, and onsite data collection. Findings show that inclinometer was the most expensive method, followed by observation and then self report; the majority of costs (90%) were borne by researchers. Study design parameters such as sample size, measurement scheduling and spacing, concurrent measurements, location and travel, and equipment acquisition were shown to have wide-ranging impacts on costs. This study provided empirical cost data for use in cost models that can facilitate decision making and planning of future studies, and can be used to investigate cost efficiency in future studies.

Keywords: cost efficiency, exposure assessment, work related musculoskeletal disorders, methods development

1. Introduction

There is widespread acceptance that not all exposure assessment methodologies are equal; most readers will be familiar with the correctness hierarchy listing direct measures followed by observation methods and then self-report [1]. This hierarchy generally forms the basis of validation studies [2] and studies modeling the determinants of exposure [3]. However, validity is not the only criterion when selecting an exposure assessment method. These studies also acknowledge that the cost of some methods prohibit measurements over large numbers of people, for example, in epidemiological studies. Despite the ubiquitous challenge of budgeting for successful research, issues of exposure assessment cost are not often represented in the literature.

A recent review attempted to summarize the state of inquiry into cost-efficiency exposure assessment, and identified only nine articles systematically addressing this area [4]. Since literature was sparse, the authors described the related but distinct notion of statistical efficiency, where researchers may use variance components to allocate measures in the most efficient way. The reviewers rightfully point out that such studies often make a series of assumptions that are not borne out in reality: assuming that all measurements have an equal cost [5], or that costs can be assessed using linear 2- or 3-stage cost models with only a few types of costs such as ‘measurement’ and ‘recruitment’ [6-8]. While non-linear cost models were recently investigated by Mathiassen and Bolin [9], that study still assumed a single 3-stage cost model. These works represent a substantial contribution to the area of cost-efficiency

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in research planning, but the cost models are expected to be too simplistic.

Much of the cost efficiency work so far has been performed with arbitrary measurement costs to demonstrate the principles. In order for researchers to make decisions about which method to use, realistic cost information is required. Despite its importance, research costs are not often discussed or reported in studies of occupational exposure. In their review, Rezagholi and Mathiassen [4] identified only two articles that explicitly listed the cost of measurement [6, 10], and only one that did so for biomechanical exposures [10]. Although unique in listing measurement costs for biomechanical measurements, the Trask et al. article also had many limitations [10]. For example, the cost estimates did not include the costs associated with recruitment, travel, or analysis, all of which represent significant contributors to total study cost. The format of the cost model also limited its applicability; rather than listing fixed and variable costs the Trask et al. article listed the average cost for all measurements in the study, thereby limiting the applicability of the cost model to situations with different numbers of subjects or repeated measurements in identical settings. Ideally, a cost model will demonstrate how measurement allocation affects the total study cost as well as the tradeoff between cost components. A complete cost model with realistic cost inputs that can be applied to multiple scenarios would be a helpful contribution to this area of research.

One of the overarching goals of our research on cost-efficient exposure assessment is to investigate the costs of exposure assessment in field-based studies of musculoskeletal risk factors. The current study used *a priori* cost tracking of all research activities during a study of trunk and shoulder posture in airport baggage handlers. Costs were assessed for three commonly-used methods of assessing daily postural exposure: self-report via questionnaire, observation via video film, and direct measurement using inclinometers. The present paper provides a comprehensive cost model for exposure assessment research, documents the monetary costs of the three exposure assessment methods, and provides a discussion comparing the costs of these methods.

2. Methods

2.1 Study design and subject recruitment

Baggage handlers from a single employer at a large Swedish airport were recruited to the study. Eligible workers included full or part-time workers, but not those on modified duties or a return-to-work schedule. Workers were stratified by workshift and invited to participate in the study in a randomized order. Workers who consented had their trunk and shoulder posture assessed for 3 full shifts using three methods: self-report via questionnaire, observation via video film, and full-shift inclinometer registration via tri-axial accelerometers. All subjects signed an informed consent form and all methods were approved by the Regional Ethical Review Board in Uppsala.

2.2 Cost model

The cost analysis presented here focuses on the data collection stage of research. For the purposes of this cost analysis, the 'project' starts with the acquisition of equipment and pilot testing and ends with the completion of all scheduled measurement days. Activities such as preliminary meetings with industry stakeholders and writing grant proposals are not included in this analysis, nor is the processing of collected data into exposure statistics, analysis of video, the statistical calculations or reporting of results to the scientific community. Measurement costs were assessed for capital including all equipment, as well as all labour involved in several different tasks: planning, training, piloting, subject recruitment, travel, and data collection.

In this study, the general model for assessing total cost for method m , C_{Tm} , included several fixed costs (denoted by \check{C}): the cost of project meetings to plan the study (\check{C}_M); the cost of administering the research aspects of the study, including documentation, budgeting, and internal correspondence, (\check{C}_A) and administration related to recruitment, including corresponding with employer and scheduling (\check{C}_R); the cost for equipment and software capital (\check{C}_E); the cost of training data collectors to use measurement method m (\check{C}_T). The model also included several variable costs (denoted by \dot{C}): the cost of traveling to the worksite (\dot{C}_V) and accommodations during overnight trips (\dot{C}_H); the cost of recruiting workers at the worksite (\dot{C}_R); and the cost of onsite data collection (\dot{C}_D). This model can be applied to any measurement method m following the general form of Eq. (1):

$$C_{Tm} = \check{C}_M + \check{C}_A + \check{C}_R + \check{C}_E + \check{C}_T + \dot{C}_V + \dot{C}_H + \dot{C}_R + \dot{C}_D \quad \text{Eq. (1)}$$

\dot{C}_V is calculated as the product of the average cost per trip \bar{c}_v and the number of trips n_t ; \dot{C}_H is calculated as the product of the average cost per night \bar{c}_H and the number of nights n_n ; \dot{C}_R is calculated as the product of the average cost of recruiting one worker \bar{c}_R and the number of workers n_w . If two researchers travel to the worksite on the same date, that is two researcher-days n_d . There is a certain amount of preparation time that must be spent irrespective of how many workers are measured, introducing a potential efficiency by measuring multiple workers on a given researcher day. To account for this, \dot{C}_D is calculated as the sum of the costs for the first worker and concurrently measured workers as in Eq (2):

$$\dot{C}_D = \bar{c}_s n_m + \bar{c}_F n_d + \bar{c}_c n_c \quad \text{Eq. (2)}$$

Where \bar{c}_s is the average cost of measurement supplies per measurement day n_m , \bar{c}_F is the average cost for the first worker measured on a researcher day n_d ; and \bar{c}_c is the average cost of concurrently measured workers n_c . The total number of concurrently measured workers in the study is the number of researcher days (n_d) where a second worker is measured, or n_d subtracted from the total number of measurement days, n_m . Therefore, the full model can be expressed as Eq (3):

$$C_{Tm} = \dot{C}_M + \dot{C}_A + \dot{C}_R + \dot{C}_E + \dot{C}_T + \bar{c}_v n_t + \bar{c}_H n_n + \bar{c}_R n_w + \bar{c}_s n_m + \bar{c}_F n_d + \bar{c}_c n_c \quad \text{Eq. (3)}$$

The constants applicable to the data collected in this study are presented in table 1.

2.2 Data collection

2.2.1 Inclinometer

Postural inclination with respect to gravity was measured using the VitaMove triaxial accelerometer system (2M Engineering, Veldhoven, The Netherlands). A recorder was placed on the trunk between the shoulder blades and one on each upper arm over the medial deltoid. Workers came in before their shift for instrumentation and calibration, then were measured during their regular work tasks for the duration of the shift. Data were downloaded to a computer and backed up on a hard drive at the end of the shift.

2.2.2 Observation

Researchers video filmed the workers continuously during one half of the shift. This involved following the workers while they performed their regular work tasks and endeavouring to capture their trunk and shoulder postures. The video was subsequently downloaded onto a computer and backup hard drive for later analysis.

Table 1
The cost model coefficients for the present study

Parameter	Value
n_t number of trips to the worksite	30
n_n number of nights spent at the worksite	38
n_w number of workers	27
n_d total number of researcher days	51
n_m number of worker-days	80
n_c number of concurrently measured workers	29

2.2.3 Questionnaires

Prior to starting their work shift, workers filled out a short, 3-item questionnaire regarding their current fatigue and body pain. After the work shift was completed, the workers filled out a post-shift questionnaire which repeated the fatigue and body pain questions, as well as including items on the amount of time spent performing specific postures and tasks during that particular shift.

2.2.4 Cost data collection

The data collection of this study was designed for prospective cost tracking rather than retrospective accounting. This meant empirical data rather than hypothetical amounts [9] and averages [10] as used in previous cost studies. Researchers' office and lab tasks such as administration, planning, training and piloting were tracked using a custom Excel macro with defined task categories, then later compiled into hours per task category for all researcher staff working on the project. Researchers' time spent travelling and recruitment or measurement tasks was tracked via paper forms, and summarized for each measurement day. All costs were standardized to Euro currency using the average exchange rate between October 2010 to March 2011. All researcher time was valued at €31 per hour with a University overhead addition of 68%. Because costs were collected for each measurement day independently, estimates of cost variability (in terms of standard deviation) are available for \bar{c}_v , \bar{c}_H , \bar{c}_R , \bar{c}_s , \bar{c}_F , and \bar{c}_c .

When determining the cost components for each method, data collection time was considered for each

method independently. In practice several methods were applied concurrently, but the cost components presented assume that researcher time is paid for the full time spent on each method without savings for multi-tasking. This is designed to facilitate decision making about single-method studies.

The study also considered which stakeholders bore the costs of research. Although most of the costs listed were borne by the researchers, the employer paid for workers to come early and stay late on each measurement day (a total of 1 hour paid non-productive time per measurement day). Employer administrators also assisted with the study and tracked their time spent on research tasks using a customized MS Excel spreadsheet.

3. Results

3.1 Study sample

Fifty (50) workers were invited to participate and 29 agreed (58%). Twenty-seven of these workers were successfully measured. A total of 80 workshifts

were collected with successful, concurrent assessments using all three methods. The questionnaire and video recording were completed successfully each time they were attempted (success rate of 100%), and the inclinometer method had a success rate of 93%. All participants were male; work shifts varied from 6 to 12 hours in length.

3.2 Study costs

Values for the cost components observed for each of the three measurement methods are presented in table 2. The cost components in table 2 summarize costs borne by all research partners. The first column in table 2 ('applicable to all methods') shows the costs that are required no matter which method is used; the total for each method represents the total study cost for applying that method, including the costs that are in the first column. The average costs observed in the study are presented in table 3. The proportion of the total study costs borne by each of the study partners (for all methods combined) is presented in table 4.

Table 2

Cost model components for three measurement methods in the current study, researcher, employer, and worker production costs combined

Cost component	Applicable to all methods	Inclinometer	Video observation	Daily exposure Questionnaire
\hat{C}_M (planning meetings)	€ 2,340,00			
\hat{C}_A (administration)	€ 2,547,55			
\hat{C}_R (recruitment administration)	€ 2,216			
\hat{C}_E (equipment)	€ 2,401	€ 6,030	€ 2,095	
\hat{C}_T (piloting and training)	€ 4,916	€ 1,777	€ 693	€ 559
\hat{C}_V (travel)	€ 8,179			
\hat{C}_H (accommodations)	€ 5,658			
\hat{C}_R (recruitment)	€ 595			
\hat{C}_D (measurement)		€ 29,995	€ 23,726	€ 7,452
C_{Tm} Total Study Cost		€ 66,657	€ 55,369	€ 36,865

Table 3

Average costs for three measurement methods, researcher, employer, and worker production costs combined (sd)

Cost component	Applicable to all methods	Inclinometer	Video observation	Daily exposure Questionnaire
\bar{c}_R (average cost of worker recruitment)	€ 22 (14)			
\bar{c}_V (average cost per trip to worksite)	€ 273(159)			
\bar{c}_H (average cost per accommodation day)	€ 149 (22)			
\bar{c}_S (average cost of measurement supplies)		€ 1		€ 4
\bar{c}_F (average cost of first worker measured)		€ 508	€ 342	€ 135
\bar{c}_C (average cost of concurrently measured workers)		€ 83(49)	€ 216 (70)	€ 9(8)

Table 4
Cost proportions borne by different research stakeholders for the present study parameters, all methods combined

Cost component	Researchers	Employers admin staff	Worker production time
\hat{C}_M (planning meetings)	€ 1.169,56	€ 1.170,43	
\hat{C}_A (administration)	€ 1.897,31	€ 754,28	
\hat{C}_R (recruitment administration)	€ 1.748,16	€ 468,17	
\hat{C}_E (equipment)	€ 10.526,36		
\hat{C}_T (piloting and training)	€ 7.686,30		€ 260,10
\hat{C}_R (recruitment)	€ 1.413,22		
$\hat{C}_V + \hat{C}_H$ (accommodations and travel)	€ 7.658,68		
\hat{C}_D (measurement)	€ 36.226,34		€ 4.161,53
C_T Total Study Cost for all methods	€ 64.093,81 (90,39%)	€ 2.392,88 (3,37%)	€ 4.421,63 (6,24%)

4. Discussion

4.1 Comparing cost of different methods

This study provided empirical cost data for use in cost models that can facilitate decision making and planning of future studies, as well as be used to investigate cost efficiency in future studies. For the current study design, exposure questionnaires were the least costly way to collect posture data, followed by observation and then inclinometer.

It is important to note that the method-specific measurement costs are not always the majority of the total study cost, since the fixed and variable costs that apply to all methods make up between 43% and 78% of the total study cost. This provides a substantially different result from previous reports of cost in ergonomic exposure assessment that disregarded travel and recruitment components, resulting in interview method costs roughly 10% that of inclinometry [10] compared to roughly 50% in the present study. Clearly this has a substantial effect on research planning and also the relative tradeoff between methods; choosing a self-report method does not necessarily mean that one can conduct 10 times as many exposure assessment for the same price; one must consider the overall logistics of the study.

4.2 The effect of logistics and planning

Study planning requires a lot of logistics, although not all aspects are reported in research literature. Decisions around sample size, measurement scheduling and spacing, concurrent measurements, and location and travel, and equipment acquisition can also have wide-ranging impacts on costs.

Sample size affects generalizability, study power, and confidence in research results, but is limited by budget constraints. The model shows explicitly the cost increase when a new worker is recruited for measurement. Retention and attrition are acknowledged problems in public health research, and it can be increasingly difficult to maintain participation with multiple follow-ups. Similarly, it may be that as the sample size approaches an exhaustive sample of the worksite, the cost of recruitment goes up (or down) rather than staying constant as in the cost model presented here. These types of non-linear relationships have been hypothesized [9], but the current study did not collect empirical data to be able to implement them.

The inclinometer had the highest fixed costs, and therefore the most opportunity to amortize the fixed equipment costs over many measurements. However, the variable costs are also high since the time demands of the inclinometer are greater than the other two methods; the researcher needs to remain at the worksite for the full shift, rather than half the shift as per the observation method or 1 hour as per the questionnaire. Although this is a conservative estimate of time required for the inclinometer, this method only requires hands-on researcher input for set-up and take-down and occasionally troubleshooting during the shift. This means the inclinometer lends itself very well to multi-tasking or to concurrent measurements. In multi-tasking researchers would analyze previously-collected data, write reports, or do administrative work during the seven hours between inclinometer set-up and take-down. If researchers were to perform useful work during the inclinometer measurements, the average cost of a day's inclinometer measurement would decrease to €175; the total study cost for an inclinometer study with the parameters of the current study would be €48,086, a savings of €18,571. In concurrent measurements, several workers would be

measured within the same workshift for the same amount of preparation, travel, and waiting time and this could yield savings. The feasibility of concurrent measurements will depend on the start times of the workers and how flexible employer and/or workers are to modifying work times to allow for set up and measurement of several workers. Our informed estimate is that 4 workers could be measured simultaneously using the inclinometer, 10 or more using the questionnaire, and only 1 additional worker for the video camera (unless the amount of recording time was shortened).

Although not explicit in the cost model, it is possible for the spacing of measurements to affect cost as well as the more well-known effects on exposure values. In the current study we chose consecutive shifts to avoid the travel costs and administrative hassle of scheduling workers on a rotating shift schedule, but the tradeoff is autocorrelation in the data. We also elected to conduct over a 3-month period during the winter, which surely impacts the type of exposures encountered and unlikely to have full generalizability to the other parts of the year. However, a year-long sampling campaign would have been cost-prohibitive, given the need to retain staff for the full year, or retrain new staff.

Travel and accommodations needs are likely to vary substantially between research studies depending on the location of the researchers and institution relative to the data collection site. The current study showed substantial variation in travel distance and cost, represented by a σ_V^2 coefficient of variation of 58%. The distances in the current study required considerable travel, and introduced a tradeoff between the total number of trips and length of stay. Naturally cost is not the only factor when planning such logistics; an additional consideration will be the tolerance of data collectors and local labour laws.

This study assumed no depreciation of the equipment cost, so the whole cost of research equipment purchase price is included in \check{C}_E . The costs presented therefore represent the situation of 'starting from scratch' and having to purchase all equipment. However, were the author group to pursue a similar study in the future, the decision between which method to select would be weighted only on the variable costs, since the equipment has already been acquired.

4.3 Who's paying? Researcher and employer-borne study costs

The majority – over 90%- of costs tracked in the current study were borne by researchers. It seems likely that potential biases would tend to overestimate this proportion, since researchers were likely to be more motivated and diligent in tracking time spent on the study. It is possible that the time tracked by employer administrators (3.4% of the total study costs) is underestimated. For example, short tasks might not be deemed 'worth tracking' but cumulatively might represent a relevant cost. When deciding whether to participate in research, information about the time and resource commitments can help manage expectations and plan resources, as well as demonstrating researchers' sensitivity to balancing business interests with research needs, the prioritization of which is different for researchers and industry stakeholders. Although informing about costs may not have a strong influence on participant recruitment, it seems likely to foster better trust and stronger relations between research stakeholders and almost certainly enhances retention or re-contact of study participants.

In the current study, employer administration and worker's production time were both borne by the employer. In other contexts, the employer might not be able to pay for workers' time, and transferring this cost (in terms of time spent or opportunity cost) onto workers is likely to affect the participation rate. To address this, some studies provide an economic incentive equivalent to wage replacement [11]. This could increase the research budget substantially; worker production time costs accounted for over 6% of the observed cost in the current study. Although workers were paid for their time when they showed up early and stayed late, a limitation of the current study's method is that it does not account for opportunity costs associated with extending the workday or filling out questionnaires during work time. Adding an hour to the workday may also affect carpooling arrangements or transit/parking habits that can change direct costs of participation; it also means less time with family or sports and leisure pursuits. These types of costs are difficult to quantify and so were not included in the current study, although they can have an impact in participants' decision making.

4.4 Method performance: another consideration for decision making

If cost were the only consideration, the findings presented here would suggest that self-report is always the best option for posture research. However, cost is far from the only criterion for selecting an exposure assessment method; researchers also need to consider the quality of the data in terms of accuracy, precision, or predictive validity in terms of health outcomes. In order to address this issue, the cost efficiency of each method must be determined by comparing the price to the performance of each method.

To determine cost efficiency, cost data (such as that contained in this report) could be combined with components of variance from collected exposure data to quantify the cost efficiency of each method and sampling schemes as described previously [4, 9]. Variance components are often used to guide allocation of measurement efforts within and between individuals [12]. Most studies investigating this issue have considered only statistical efficiency, not measurement cost [4]. However, statistical optimization could yield a substantially different study design than cost efficient optimization in certain cases [8]. For example, when within-worker variance is high and recruitment costs are high, multiple measures per worker seems to be a sampling strategy that improves precision as well as cost [6, 9]. In general, previous cost-efficiency studies have shown that for simple cases, variance components and costs of a certain structure can be optimized, but the complexity of the cost model, the introduction of non-linearity, and the degree of uncertainty in some components may preclude a fully optimized model and instead favour an iterative approach.

4.5 Performance of the cost model

The accounting protocols used in this study allowed estimation of variability in average costs, and variability tended to be high. The coefficient of variation (CoV) in recruitment and travel were both over 50%, demonstrating that these costs are influenced by other factors than just the number of workers recruited or number of trips. The cost for concurrently measured workers was also highly variable (CoV = 32-88%), a result of the varying amount of time required to complete an additional measurement. Together, the standard deviations of

the average costs give some insight as to the stability of total study cost if the study were to be repeated, introducing the notion of confidence intervals around a projected study cost. The certainty of cost estimations could be a rich avenue for future research.

With nine types of costs included, it is worth considering whether the cost model could be simplified without hampering its performance. For example, the cost of supplies was very low, with an average cost of €0-4 and a total cost of less than 1% of the total study cost. Similarly, recruitment costs accounted for less than 2% of the total study cost. These costs had so little impact on during decision making that they are probably not worth tracking. The most important cost components are those involving researcher time, not other stakeholders' time, travel, or materials and equipment. On analyzing costs, it becomes apparent that 'time is money.'

There are a number of other 'hidden' costs that were not explicit in the model. For example, although it is likely to be negligible in relation to total study costs, there are energy costs associated with computer use and recharging batteries for measurement equipment that is not accounted for in a distinct term. Similarly, the fixed costs of capital investments, \dot{C}_E , includes measurement equipment used for the project but not the University infrastructure. Instead energy and infrastructure costs were considered to be included in the University overhead assessed to researcher work time. It is a limitation that other researchers cannot separate institutional overhead components, but researcher time values could be adjusted to apply different overhead structures.

This data presented do not currently include the costs related to post-processing and analyzing collected data into postural exposure variables. These costs include all tasks between data collection and statistical analysis, including data entry for paper questionnaires, data processing, visual inspection and quality control for inclinometer data, and observer time spent recording postures from video still frames. A recent study investigating the cost-efficiency of different observation sampling protocols suggests these costs can be substantial [13]. Since processing and analysis costs could comprise a considerable portion of total research costs, the comparisons between methods could evolve as these components are included.

Some time was spent multitasking, and it is difficult to separate the time spent on each method. Although it would seem that the inclinometer took the most preparation time, it is not always possible to separate how much time was spent on what. For example, downloading the inclinometer and video data while the questionnaire was being filled out, or coming in early to set up equipment and the meeting area so that things would run smoothly when the worker arrived. For this reason, the time estimates for each method and especially the questionnaire could be overestimated. Conversely, when questionnaire methods are applied alone, the time it takes to identify a participating worker and introduce an instrument is non-trivial and also not explicitly accounted in our data, so overestimates on the researcher time spent on the questionnaire are likely minimal.

Future research should investigate not only the price, but also the cost efficiency of the exposure assessment methods in terms of value outputs like precision and bias of the resulting information.

4.6 Conclusion

The current study addresses research gaps in the area of cost efficiency [4] and improves on previous studies of cost [10] by implementing prospective data collection, a comprehensive set of cost components, and acknowledging who bears the costs. Findings show that inclinometer was the most expensive method, followed by observation and then self report; the majority of costs were borne by researchers.

The cost models and cost components for the three methods inform the design of future ergonomics field research and are intended to be used as a research planning tool. The division of the model into components means that researchers use information about the estimated travel costs and proposed sampling strategy to tailor costs for a novel study, allowing them to allocate resources more efficiently. This allows for appropriate economic decisions on the use of limited resources when designing ergonomics studies in working life.

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