Ergonomic Assessment Methods for the Evaluation of Hand Held Industrial Products: A Review

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***Abstract*—In the segment of industrial products, hand held products occupy a major section. An important issue in design of these products is to identify the factors that lead to human comfort and those leading to discomfort. The aim of this paper is to discuss some approaches for product evaluation and to discuss their significance in designing better products. Usability testing is increasingly being realized as an important tool for evaluating products. Comfort and discomfort assessment has been a topic of major concern when comparing and evaluating products. The understanding of the two terms in the context of product evaluation and the methods for evaluating comfort and discomfort experience have also been discussed. The work reviewed provides a solid foundation on which any future research for product development and assessment can be performed and analyzed.**

***Index Terms*—comfort, discomfort, ergonomics, hand held industrial products (HHIPs), usability**

I. INTRODUCTION

DUE to the globalization of the industrial sector and an increasingly competitive market environment, new products must meet more requirements than before to fulfill the expectations of the users. The product must meet not only functional and aesthetic requirements, but ergonomic quality requirements as well. It has been frequently seen that the choice of a product is dependent on the human comfort it offers in relation to the environment. An important issue in ergonomic design of products is to identify the factors that lead to human comfort and discomfort.

Individuals use their hands and fingers in everyday activities in both the workplace and home. Hand-intensive tasks require diverse and sometimes extreme levels of exertion, depending on the action, movement or manipulation involved. Hand held industrial products (HHIPs) have been developed over thousands of years to make many everyday tasks easier, from simple hunting tools to modern human computer interfaces [1]. The design of HHIPs is one of the most popular and challenging jobs in the present day scenario. Presently, products such as various powered and non-powered hand tools, as well as HHIPs used during activities of daily living (ADL) are being designed conventionally with a focus primarily on their functional and aesthetic aspects. Bad design of HHIPs and their usage for a long time may cause early hand fatigue and different hand and arm related musculoskeletal injuries. It has been observed that during the use of HHIPs, the characteristics of the surface in contact with human hand directly affect the comfort and discomfort of the user [2]. From the view point of design, evaluation of the psychological, morphological, physiological and biomechanical behavior of the users during the product use could significantly help in improving the product quality and its usability. Also, ergonomically well-designed hand held industrial products and tools may reduce the risk of occupational injuries significantly.

Powered hand tools are the most common HHIPs found in many industrial work situations. Also, non-powered hand tools such as hammers, screwdrivers, wrenches, hacksaws, pliers, etc. still have its own importance in different industries and daily life situations [3]. Each of these two categories of HHIPs has some common and some different factors underlying their usage experience. Therefore, these tools need to be studied separately and carefully in order to provide customized product solutions. Putz-Anderson [4] has suggested that a tool should be adapted to the task rather than having the worker adapt to a general-purpose tool. Care also needs to be taken to include design features so as to reduce the existing limitations in hand tools. Kadefors et al. [5] have shown that by improving the ergonomic properties of hand tools, the health of users and their job satisfaction might be positively affected. Unnatural postures and repetitive forceful exertions are the major risk factors for hand/wrist injuries. These factors may be reduced via ergonomic design/redesign of the HHIPs [6].

Since long, researchers have shown sincere interest in the ergonomic design of hand tools [2]-[3], [5]-[6]. Yet, till date there is no such unified approach to design HHIPs that could assure increases in productivity and health [7]. It is evident that the use of HHIPs can lead to accidents, overexertion injuries and discomfort when poorly designed or badly used [8]. Therefore, there exists enormous scope for better-designed HHIPs that contribute to better performance and greater comfort. Good performance and

Manuscript received March 23, 2013; revised April 11, 2013.

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comfort are considered under desired qualities when it comes to product selection. In the use of HHIPs, comfort could be associated with positive feelings of reliability, safety, ease, restfulness and satisfaction, whereas discomfort might be associated with negative experiences of pain, pressure, hardness, roughness and irritation. Studies related to different HHIPs in terms of comfort and discomfort, such as hand drilling machine, garden tools, handsaws, pliers, screwdrivers, wire-tying hooks, etc. have been done in the past [2]-[3], [5]-[6].

The aim of this paper is twofold: (1) to review literatures related to assessment of hand comfort and discomfort while operating various HHIPs, and (2) to present a sound discussion on various techniques/tools adopted by the researchers for the design/redesign of HHIPs that increases the performance, as well as comfort in arms, shoulder and different hand regions. The knowledge gathered in the work provides a sound basis to design/redesign HHIPs superior in terms of ergonomics and usability.

Section II of the manuscript discusses in brief about the various subjective and objective measurement techniques employed for the assessment of comfort and discomfort during the use of HHIPs. Section III presents the comfort and discomfort experiences by the user while using the hand tools. In Section IV, effects of vibration and wrist deviation are discussed for various HHIPs. Finally, concluding remarks are presented in Section V.

TABLE I
COMFORT QUESTIONNAIRE FOR HAND TOOLS (CQH) [11]

Screw driver	Totally disagree	Disagree somewhat	Agree Somewhat	Totally agree
Reliable	1	2	3	4
Functional	1	2	3	4
Easy in use	1	2	3	4
Safe	1	2	3	4
Product quality	1	2	3	4
Easy to carry	1	2	3	4
Handle easily	1	2	3	4
Muscle cramp	1	2	3	4
Working posture	1	2	3	4
Pain in muscle	1	2	3	4
Force apply	1	2	3	4
Handle hardness	1	2	3	4
Blisters	1	2	3	4
Tactile feeling	1	2	3	4
Irritation	1	2	3	4
Numbness in finger	1	2	3	4
Good fit in hand	1	2	3	4
Force exerted by tool	1	2	3	4
Peak pressure in hand	1	2	3	4
High quality tool	1	2	3	4
Friction in hand	1	2	3	4
Handle shape	1	2	3	4
Sharpness	1	2	3	4
Pleasurable	1	2	3	4
Slippery handle	1	2	3	4
Weight of tool	1	2	3	4
Solid design	1	2	3	4
Nice Colour	1	2	3	4
Roughness on hand surface	1	2	3	4
Look professional	1	2	3	4

II. ROLE OF SUBJECTIVE AND OBJECTIVE MEASUREMENTS

Different subjective and objective methods have been employed by researchers in the past to assess comfort/discomfort while working with HHIPs.

A. *Subjective Methods*

Subjective measurements are most common when hand tools are evaluated with respect to comfort and discomfort. Most of them are focused on discomfort felt by the user. Although there have been questions raised on the validity of subjective methods, Johnson [9] has emphasized the usefulness of subjective usability evaluations of hand tools for comfort, productivity, and ease of use. Subjective comfort and discomfort in case of HHIPs are commonly assessed using inputs on comfort questionnaire for hand tools (CQH) as shown in Table I [10]-[12], rating scales for perceived exertion (RPE) [13]-[17], using pain maps, measuring pain and discomfort ratings [18]-[20] and local perceived discomfort (LPD) [21]-[24]. Subjective evaluations have some clear disadvantages: they require a large number of subjects and are therefore time consuming [25] and they are influenced by personal preferences [26]. There are some common known sources of unreliability of using subjective measures, like time error and context effects [27]. Therefore, objective measurements are used in addition to subjective measurements.

B. *Objective Methods*

Objective methods help in verifying the authenticity of the subjective tests based on our knowledge of the physical and biomechanical limitations and capacities of the human body. Objective methods also help in providing scientific logic and reason behind the subjective responses. Different responses from the users could then be attributed to the levels of different physiological and biomechanical responses of the human body. On most occasions, some objective parameters are recorded in addition to the subjective inputs from the users. The choice of the parameters to be gathered is based on the kind of research being conducted and also on the body parts involved while performing the task. Measuring hand anthropometry is a key activity which is commonly performed in different hand related research work. Researchers have performed different studies such as investigation of the optimum grip span relative to an individual's hand anthropometry (ROGS) for an isometric power grip exertion [28]. Techniques used for the investigation are maximum voluntary isometric grip force (MVGF), muscular activity (EMG) and subjective rating (SR) analysis. In a study, Kwon et al. [29] identified key dimensions for the development of a glove sizing system by analyzing the relationships between hand dimensions, and demonstrated the construction process of glove sizing systems based on the selected key dimensions. In another study, Choi et al. [30] used Alignate method to archive Korean children's palm surface area (PSA) data and to calculate an optimized formula for estimating PSA. Recently, Yu et al. [31] proposed a new hand measuring approach by using 2D and 3D scanning. The method was evaluated through comparisons with manual measurements of anthropometry.

Objective measurements such as measurement of pressure pain threshold (PPT) [32]-[33], wrist and body posture and deviations [34]-[42], grip strength/force/torque [43]-[46],

TABLE II
STUDIES TO ASSESS AND EVALUATE HHIPS

References	Tools/HHIPs evaluated	Assesment Methods
[2]	Saw, hammer, screwdriver	#10,#21,#25,#28,#37
[3]	Box lifting task	#16,#20,#37,#45,#54
[6]	Garden tools - loppers, hedge shears, shovels, leaf rakes, hoes, garden rakes	#25,#28,#29,#33,#64
[10]	Pistol grip and in-line powered screwdriver	#2,#4,#11,#20,#27,#30,#64
[11]	Chopsticks	#1,#10
[12]	Angle nut runners	#20,#27,#29,#33,#44,#45,#51,#53,#54
[13]	Force measuring device	#12,#26,#29,#52,#56
[14]	Mason's trowel	#3,#29
[15]	Spray gun	#4,#22,#29
[16]	Chopsticks	#7,#15,#17,#20,#22,#28,#29,#30,#38,#39
[17]	Flat file	#3,#22,#28,#29,#43,#56
[18]	Spray gun	#19,#45,#55
[19]	In-line electric screw driver	#8,#28,#30,#49
[20]	Snow shovel	#2,#19,#20,#25,#40,#45,#55
[21]	Poultry deboning knife	#27,#28,#37,#44
[22]	Upholstery tools, spray guns, random orbital sanders	#25,#31
[23]	Pliers and wire-tying hand tool	#3,#28
[24]	Pliers, cordless powered screwdrivers	#3,#11,#22,#37,#48,#49
[33]	Knife	#2,#4,#5,#19,#25,#36,#54
[34]	Scissors	#4,#20,#46,#47,#57
[35]	Pliers	#2,#12,#44,#50,#51
[36]	Powered nut drilling tools	#4,#11,#23,#39,#54,#61,#64
[37]	Bar clamp	#25,#64
[38]	Hacksaw	#25,#28,#39,#33,#34,#54,#64
[39]	Buffing machines, mopping systems, vacuum machines	#1,#4,#49,#56,#57
[40]	Laparoscopic grasping tool	#1,#11,#42,#56,#57
[41]	Three pin electrical plug (assembly task)	#33,#44,#59
[42]	Cube shaped part (pick-and-place task)	#20,#25,#51,#59
[43]	Screwdrivers	#14,#25
[44]	Handsaws	#20,#50,#58
[45]	Buckets	#25,#45,#52,#64
[46]	Weaving comb, knife and scissors	#20,#25,#64
[47]	Chopsticks	#16,#25,#60
[48]	Rope (vertical pulling task)	#20,#25,#52,#64
[49]	Chopsticks	#19,#25
[50]	Liquid containers	#16,#20,#25
[51]	Scissors	#14,#25,#44
[52]	Screwdrivers	#25,#28,#64
[53]	Graphic order terminal (GOT)	#25,#37,#44
[54]	Arborist handsaws	#5,#25,#28,#33
[55]	Surgical scalpels	#25,#44,#54,#64
[58]	Nut runners	#20,#27,#33,#54,#58
[59]	In-line pneumatic screwdriver	#11,#13,#17,#18,#22,#27,#32,#33,#35,#48,#49,#54,#59
[60]	Steel fixture with grip	#51,#53,#54

finger force [47]-[50], muscular effort (%EMG) [51]-[55] and hand pressure magnitude and distribution [56]-[57] are some frequently performed methods for HHIPs comparison and evaluation.

In addition to subjective and objective methods of product and task evaluation, usability methods are extensively used in order to study the performance of the users while using the product. Different metrics such as

NOTE: FOR TABLE II

S. No.	Details of Assessment Tools / Methods
#1	Anthropometric measurements.
#2	Arm postures, positions, displacement, speed, acceleration. Deviation.
#3	Body/body-part discomfort. Whole body (WBD), shoulder (SD), upper arm (UAD), Using category Partitioning Scale (CP-50). Visual analog scale (VAS) 0-100 mm line.
#4	Body/body-part posture, movement, position, velocity, acceleration.
#5	Center of pressure (CoP) displacement.
#6	Checklists for tool assessment.
#7	Checklists for workplace assessment.
#8	Cognitive discomfort.
#9	Complaints arising from tool use.
#10	Comfort questionnaire. Comfort questionnaire for hand tools
#11	Direct observation.
#12	Endurance. Fatigue.
#13	Environmental data. Air temperature, humidity.
#14	Ergonomic quality rating.
#15	Expert assessments.
#16	Finger force.
#17	Focus groups.
#18	Follow-up interviews.
#19	Force exerted by tool. Reaction forces. Torque, impulse
#20	Hand grip strength and forces. Torque, impulse.
#21	Hand pressure.
#22	Heart rate (HR). Workload.
#23	Load moment on the back.
#24	Maximum acceptable exertion.
#25	Maximum voluntary contractions (MVC). Electromyography (EMG).
#26	Oxygen consumption. Minute ventilation.
#27	Perceived comfort.
#28	Perceived discomfort. Locally perceived discomfort (LPD). Body Part Discomfort Scale (BPD).
#29	Perceived exertion. rating of perceived exertion (RPE). Using the Borg 10-point ratio rating scale.
#30	Perceived pain. Using pain maps.
#31	Perceived fatigue. Borg CR-10 scale.
#32	Perceived safety.
#33	Perceived ease of use. Difficulty.
#34	Perceived satisfaction.
#35	Perceived speed of use.
#36	Pressure pain threshold (PPT).
#37	Productivity. Number of repetitions, tasks. Frequency.
#38	Push-pull force at tool.
#39	Questionnaire to understand the work tasks.
#40	Reach distance.
#41	Reaction forces.
#42	Standards questionnaires. Nordic MSQ.
#43	Subjective ratings of tasks.
#44	Subjective ranking of tools.
#45	Subjective discomfort ratings
#46	Subjective quantification of forces.
#47	Subjective quantification of weights.
#48	Subjective preference ratings. Using Borg CR-10 scale. Likert's scale.
#49	Task analysis. Demands.
#50	Task efficiency.
#51	Task precision.
#52	Task repetitiveness.
#53	Task stability.
#54	Task time.
#55	Tool displacement/movement. Distance, angle, speed.
#56	Tool specifications. Weight, texture, shape, dimensions.
#57	Type of grip.
#58	Usability testing.
#59	User opinions. Questionnaire.
#60	Vibration, Transmission, Vibration energy absorption (VEA), Temporary threshold shift (TTS).
#61	Visual examination of ergonomic qualities.
#62	Work height.
#63	Work quality.
#64	Wrist deviation. Position, velocity, acceleration.

safety, reliability, ease of use [16]-[17], [52], [54], [58]-[59]; task efficiency, precision, stability, duration [12], [35], [42], [44], [60], etc. have been employed by researchers in the past to evaluate the usability of different kinds of products. For the measurement of the parameters of the various metrics responsible for the assessment of usability testing, parameters could be both subjective and objective in nature. The data could be collected using different rating scales and ranking procedures, by direct observation or through equipment like algometer, dynamometer, goniometer, heart rate monitor, accelerometer, etc.

Some of the studies conducted in the past and the evaluation techniques used for the ergonomic assessment of HHIPs are grouped in Table II. These details are relevant in understanding the kind of research prevailing in the field of assessment of HHIPs and may help in the CAD based ergonomic design of these products.

III. COMFORT/DISCOMFORT EXPERIENCES

User participation is needed in product development because users are the only ones who can evaluate comfort and discomfort during normal use of a product [1]. Discomfort and comfort experiences are very subjective, and the best way to measure discomfort is therefore by questioning the users. Comfort experience is considered in only a few hand tool evaluation studies [10]-[12] as the comfort experience is relatively difficult to perceive than a discomfort experience. According to Kuijt-Evers et al. [2] comfort is mostly determined by functionality and physical interaction while using hand tools. There also exists the possibility that a normal condition, without any discomfort might be termed as comfortable by the user. Therefore, definitions or levels of comfort are difficult to judge.

There exist strong correlations between perception of comfort or discomfort and the different qualities which are considered important in a product. In a study to assess the relationship between productivity and discomfort using scrapers, the scraper requiring fewer scraping motions was considered to be more comfortable by a group of painters [61]. It was also observed that such a scraper caused significantly less discomfort in the upper extremity. In the context of hacksaws, Das et al. [53] also found a higher productivity with the hack saw which was subjectively assessed as more comfortable. A reasonably linear relationship was found between load on the body and the discomfort in a body region [62], as well as between discomfort and holding time [63]. Since work studies are highly contextual in nature, researchers are still coming up with novel methods to assess and evaluate comfort and discomfort experiences.

IV. EFFECTS OF VIBRATION AND HAND DEVIATION

Vibration is also a major cause of occupational diseases and injuries at work and is one of the reasons behind subjective discomfort at work. Researchers have performed various studies and collected operating data of different parameters associated with vibration-based products, which are essential in the ergonomic design of HHIPs. Kihlberg et al. [18] studied the dynamic response of the hand/arm system due to exposure of two types of vibrations, one from an impact hammer and one from a grinder. The dynamic responses studied were driving point impedance, transfer function from handle to finger, wrist and elbow. The energy per time (dissipated power) absorbed in the hand-arm system as well as the influences of grip and push forces on the impedance were also studied. Maeda et al. [64] have studied the hand-held vibration exposure in the working surface, and its effect on the temporary threshold shift (TTS) in vibrotactile perception threshold at the fingers. Vergara et al. [65] in their study of 70 different tools used in different industrial sectors interviewed ninety workers about their perception of vibration and the symptoms of diseases related with hand vibration. The vibration transmitted to the hand–arm system was measured using a triaxial accelerometer and the signal was recorded with a human vibration meter. Xu et al. [66] investigated the characteristics of the vibrations transmitted to the wrist and elbow in the impact wrench operation and later compared the on-the-wrist and on-the-elbow vibration measurement methods.

Deviation of wrists during the operation of a HHIP is an important determinant of the risk of injury, disorders, as well as the subjective discomfort experience. In a study of wrist positions and movements among female operators in a repetitive, non-forceful industrial quality-control work while conducting a physical examination, Arvidsson et al. [67] concluded that repetitiveness and the high velocities are the likely causes for the high prevalence of disorders in the wrists/hands among the operators. Chen et al. [68] utilized a portable data logger to measure the wrist angles and forearm flexor and extensor EMG of 21 hairstylists to study ergonomic risk factors for the wrists of hairdressers. It was found that relatively higher force exertion and wrist velocity of female hairstylists combined with prolonged exposure may account for the higher rate of hand/wrist pain in female hairdressers than in male barbers. Khan et al. [69] investigated the combined effects of forearm rotation, radial/ulnar deviation and flexion/extension on discomfort score for two levels of frequency in a repetitive wrist flexion task.

Some of these researches provide subjective results which provide a better insight into how actually do the users perceive the task and the tools involved during performing the task. Some of the studies are purely based on measuring the objective parameters associated with the task being performed using the tools. Then there are studies which involve measuring both the objective data and subjective responses of the users. This helps in understanding how different objective parameters influence the user experience during the tasks and tool use. The methodology followed and the results obtained during such product evaluation studies are also very useful as many of such researches serve as benchmarks for any future researches in the field of product design.

V. CONCLUSION

The discussion on the subjectivity and the factors underlying comfort and discomfort experience could be endless. This is due to the fact that there is no absolute way in which one could measure or define comfort and discomfort. The researchers could only try to maximize the comfort and minimize the discomfort experiences based on expert knowledge in their respective fields of product development and evaluation.

Researchers have had different opinions on the relationship between comfort and discomfort. These are two distinctly judged experiences. Authors suggest discomfort can be associated with the physical characteristics like the posture, stiffness, fatigue, etc. It could be assumed that comfort will be felt when more is experienced than expected. In the case of absence of discomfort, there is a strong possibility that nothing is experienced. Comfort has been related to luxury, relaxation or being refreshed. Therefore, it is safe to assume that for case specific basis, definitions of comfort and discomfort might vary. There exists a possibility that mathematical models of comfort and discomfort could be developed by utilizing the experimental data from different subjective and objective evaluations of specific HHIPs. These numerical definitions can be used to design/redesign HHIPs in a virtual environment using a computer aided design (CAD) framework. Such a model also provides an opportunity for traditional or modified forms of optimization techniques to be adopted. As a result, superior products could be developed by integrating ergonomics, usability and CAD framework.

Human society has reached a state where greater emphasis on maximizing comfort and minimizing discomfort is an important criteria while designing products. The methods of ergonomic and usability evaluations based on comfort/discomfort experiences for HHIPs as discussed in the manuscript provides valuable inputs to the process of product design and evaluation.

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