CHAPTER 15
ERGONOMIC FACTORS IN DESIGN

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15.1 ERGONOMICS

A widespread increase in the availability of technology in the second half of the twentieth century has meant that more and more people come in contact with a variety of product designs on a daily basis. Regardless of this increase in the number and types of human users, many engineers still concentrate their design efforts on the machine or system alone, forcing the user to adjust to fit the product. Such readjustments on the part of the user can lead to discomfort and dissatisfaction with the design, as well as more serious effects, such as safety hazards and personal injury.

Ergonomics (also called human factors) is an applied science that makes the user central to design by improving the fit between that user and his or her tools, equipment, and environment. Key here is that designs are developed to fit both the physiological and psychological needs of the user. Ergonomists examine all ranges of the human interface, from static anthropometric measures and movement ranges to users' perceptions of a product. This interface involves both software (displays, electronic controls, etc.) and hardware (knobs, grips, physical configurations, etc.) issues.

Ergonomics grew into a distinct scientific discipline during the second world war. What began as a form of engineering (human engineering or human factors engineering) has come to encompass a wide range of interdisciplinary professions, including psychology, industrial design, medicine, and computer science. Its practitioners' range in focus includes concept modeling and product design, job performance analysis, functional analysis, workspace and equipment design, computer interfaces, environment design, and so forth.

15.2 HUMAN PERFORMANCE

The true basis of ergonomics is understanding the limitations of human performance capabilities relative to product interaction. These limitations are either physical or cognitive/perceptual in nature, but all address how people respond to man-made designs. Such interface analysis is crucial to establishing a safe and effective system of operation or environment for the user.

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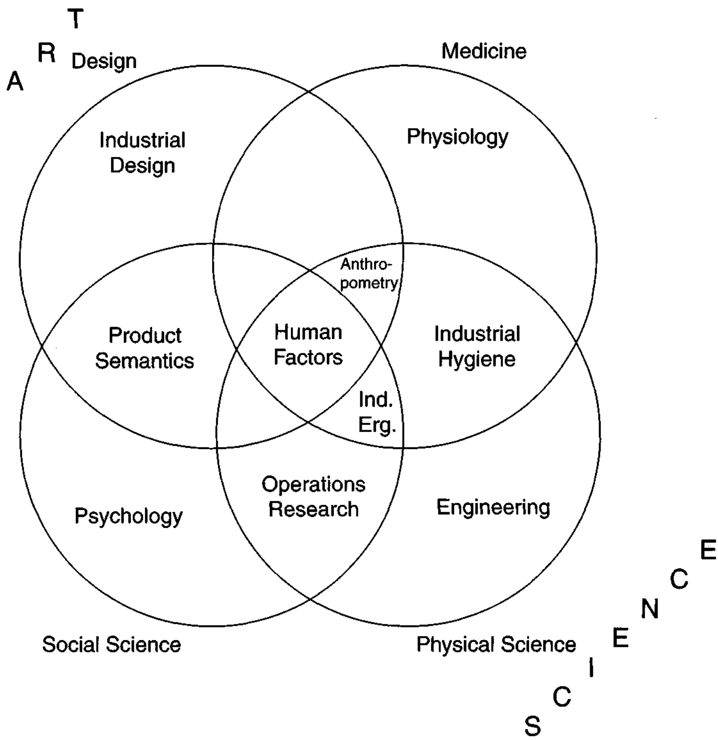


Fig. 15.1 General interdisciplinary nature of human factors with selected examples (from Ref. 1, p. 90. Reprinted by permission).

15.2.1 Physical Ergonomics

A thorough understanding of the physical characteristics of a wide range of people is essential to any product that is designed for human use. When analyzing design relative to human performance, ergonomists study static anthropometric data, which includes sizing percentiles (e.g., lengths, measurements) of a wide range of populations, including gender, age, race, and other such factors. Ranges of joint motions, strengths, and grips for varying human percentiles are also reviewed. These data serve as valuable information to designers and help ensure the final product will physically fit the targeted end-user, be it a child, the aged, or a particular racial population, and so forth.

15.2.2 Perceptual and Cognitive Ergonomics

Proper fit of a product to a user does not end with the physical interface. The perceptual and cognitive demands a product places on a user must also be examined. Note that a great misconception underlying these capabilities is that they address emotive responses of the user. However, neither are qualitative findings; both types offer fact-based, quantitative data to be used in product development.

Perceptual responses are those filtered through one or more of the five senses, such as tactile and auditory feedback of controls. Cognitive responses are based on logic, reason, and how users process information. Cognitive issues include intuitiveness of control features and functions as well as icon representation and label comprehension.

15.3 THE DESIGN PROCESS

Implementing an ergonomics program can help ensure a product's successful transition from the drawing board to the end-user. However, human factors cannot be examined in a vacuum. Ergonomists must work directly with designers and engineers throughout the entire design development process, each providing feedback to the other during concept development and testing. In addition to standard ergonomic analyses, design research should be conducted with targeted end-users to identify design problems that are often overlooked by the engineer, who examines the product only within the design environment. Such end-user research serves to measure a design's overall efficacy on a wide range

Table 15.1 Body Dimensions of U.S. Civilian Adults, Female/Male, in cm[a]

	Percentiles			
	5th	50th	95th	SD
Heights				
(f above floor, s above seat)				
Stature ("height")^{f}	152.78/ 164.69	162.94/ 175.58	173.73/ 186.65	6.36/6.68
Eye height^{f}	141.52/ 152.82	151.61/ 163.39	162.13/ 174.29	6.25/6.57
Shoulder (acromial) height^{f}	124.09/ 134.16	133.36/ 144.25	143.20/ 154.56	5.79/6.20
Elbow height^{f}	92.63/ 99.52	99.79/ 107.25	107.40/ 115.28	4.48/4.81
Wrist height^{f}	72.79/ 77.79	79.03/ 84.65	85.51/ 91.52	3.86/4.15
Crotch height^{f}	70.02/ 76.44	77.14/ 83.72	84.58/ 91.64	4.41/4.62
Height (sitting)^{s}	79.53/ 85.45	85.20/ 91.39	91.02/ 97.19	3.49/3.56
Eye height (sitting)^{s}	68.46/ 73.50	73.87/ 79.20	79.43/ 84.80	3.32/3.42
Shoulder (acromial) height (sitting)^{f}	50.91/ 54.85	55.55/ 59.78	60.36/ 64.63	2.86/2.96
Elbow height (sitting)^{s}	17.57/ 18.41	22.05/ 23.06	26.44/ 27.37	2.68/2.72
Thigh height (sitting)^{s}	14.04/ 14.86	15.89/ 16.82	18.02/ 18.99	1.21/1.26
Knee height (sitting)^{f}	47.40/ 51.44	51.54/ 55.88	56.02/ 60.57	2.63/2.79
Popliteal height (sitting)^{f}	35.13/ 39.46	38.94/ 43.41	42.94/ 47.63	2.37/2.49
Depths				
Forward (thumbtip) reach	67.67/ 73.92	73.46/ 80.08	79.67/ 86.70	3.64/3.92
Buttock–knee distance (sitting)	54.21/ 56.90	58.89/ 61.64	63.98/ 66.74	2.96/2.99
Buttock–popliteal distance (sitting)	44.00/ 45.81	48.17/ 50.04	52.77/ 54.55	2.66/2.66
Elbow–fingertip distance	40.62/ 44.79	44.29/ 48.40	48.25/ 52.42	2.34/2.33
Chest depth	20.86/ 20.96	23.94/ 24.32	27.78/ 28.04	2.11/2.15
Breadths				
Forearm–forearm breadth	41.47/ 47.74	46.85/ 54.61	52.84/ 62.06	3.47/4.36
Hip breadth (sitting)	34.25/ 32.87	38.45/ 36.68	43.22/ 41.16	2.72/2.52
Head Dimensions				
Head circumference	52.25/ 54.27	54.62/ 56.77	57.05/ 59.35	1.46/1.54
Head breadth	13.66/ 14.31	14.44/ 15.17	15.27/ 16.08	0.49/0.54
Interpupillary breadth	5.66/ 5.88	6.23/ 6.47	6.85/ 7.10	0.36/0.37
Foot Dimensions				
Foot length	22.44/ 24.88	24.44/ 26.97	26.46/ 29.20	1.22/1.31
Foot breadth	8.16/ 9.23	8.97/ 10.06	9.78/ 10.95	0.49/0.53
Lateral malleolus height^{f}	5.23/ 5.84	6.06/ 6.71	6.97/ 7.64	0.53/0.55
Hand Dimensions				
Circumference, metacarpale	17.25/ 19.85	18.62/ 21.38	20.03/ 23.03	0.85/0.97
Hand length	16.50/ 17.87	18.05/ 19.38	19.69 21.06	0.97/0.98
Hand breadth, metacarpale	7.34/ 8.36	7.94/ 9.04	8.56/ 9.76	0.38/0.42
Thumb breadth, interphalangeal	1.86/ 2.19	2.07/ 2.41	2.29/ 2.65	0.13/0.14
Weight (in kg)	39.2[b]/ 57.7[b]	62.01/ 78.49	84.8[b]/ 99.3[b]	13.8[b]/12.6[b]

[a] Adapted from U.S. Army data reported by Gordon et al. (1989) (from K. Kroemer, H. Kroemer, and K. Kroemer-Elbert, *Ergonomics: How to Design for Ease and Efficiency,* p. 30. ©1994. Reprinted by permission of Prentice-Hall, Englewood Cliffs, NJ).

[b] Estimated.

Note: In this table, the entries in the 50th percentile column are actually "mean" (average) values. The 5th and 95th percentile values are from measured data, not calculated (except for weight). Thus, the values given may be slightly different from those obtained by subtracting 1.65 SD from the mean (50th) percentile, or by adding 1.65 SD to it.

of user perception and knowledge levels. Resulting data can provide a tangible starting point upon which design revisions or new product concepts can be made.

15.4 DESIGN RESEARCH

A core component of a successful product design is understanding the wants and needs of the product's end-users. Therefore, talking with target customers to gain insight into their requirements is a logical step in concept development. Unfortunately, most manufacturers and engineers approach this issue through "gut-feeling" guesswork — fabricating a list of items or issues based on the premonitions of the development team or head of manufacturing. This method of design development is doomed from its inception, as engineers and manufacturers are often so far removed from their customer base that the resulting products never meet users' requirements or expectations.

Other times, manufacturers circumvent actual end-user research in lieu of product assessment by their marketing department. This form of "research" is extremely qualitative and often unsubstantiated by end-user feedback. Worse yet is when manufacturers base product design requirements on results of a survey of sales personnel. It is generally believed that because sales personnel are on the floor daily with customers, they have insight into customers' wants and needs. However, such methods can be disastrous, as sales representatives are not trained to observe and categorize human behavior, as many human factors specialists are.

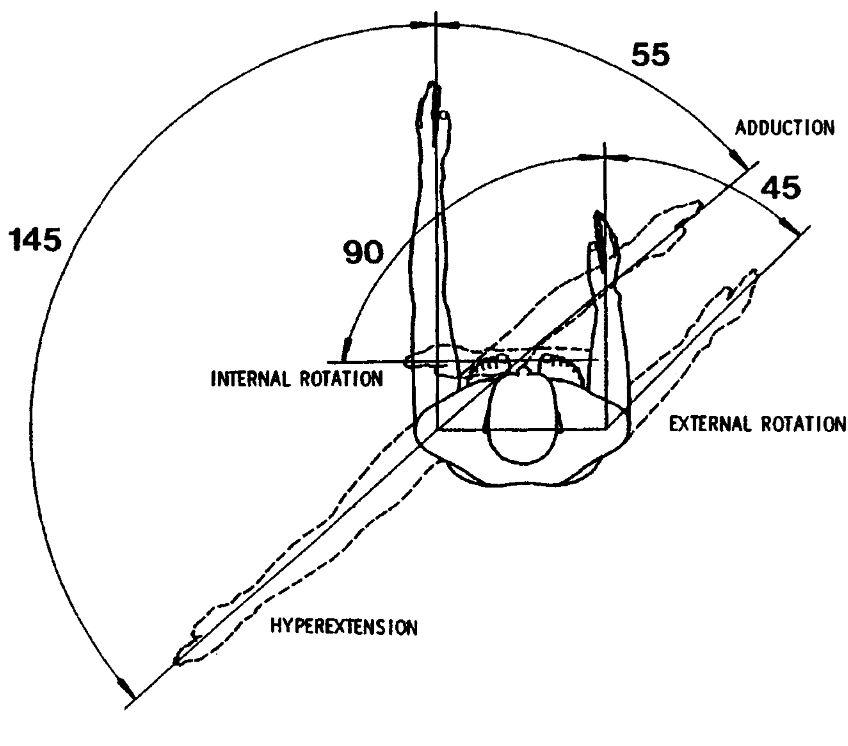
15.5 ERGONOMIC ANALYSES

Ergonomic assessments successfully define special requirements of unique user groups by providing a comprehensive assessment of the degree of compatibility between the user, the product, and the user's workspace. Data collected include empirical measures of workspace envelopes, task and link analyses (used to identify inefficiencies in the conduct of work, illogical procedures, and hazards), and definitions of anthropometric requirements (the dimensions of the human body). Several types of ergonomic analyses are listed below.

15.5.1 Anatomical Analysis

An anatomical analysis is the study of the interaction between a product and various anatomical features of the user's body (e.g., the musculoskeletal system, nerves, veins and arteries, joints, etc.). The goal of this analysis is to identify biological constraints for design that, if exceeded, may lead to user discomfort, stress, strain, pain, or occupational disability. Typically, a product's effect on the muscular, skeletal, nervous, and circulatory systems is explored.

Design programs in which this type of analysis is especially important are those that involve large forces being exerted, rapidly repeating body motions, and/or high pressure on a portion of the user's anatomy. An anatomical analysis allows ergonomists to identify potentially harmful effects of the use



SHOULDER

Fig. 15.2 Selected examples of range of joint motions: upper extremities (from B. G. Rutter, *Dynamic Anatomical Anthropometry*. ©1981. Reprinted by permission).

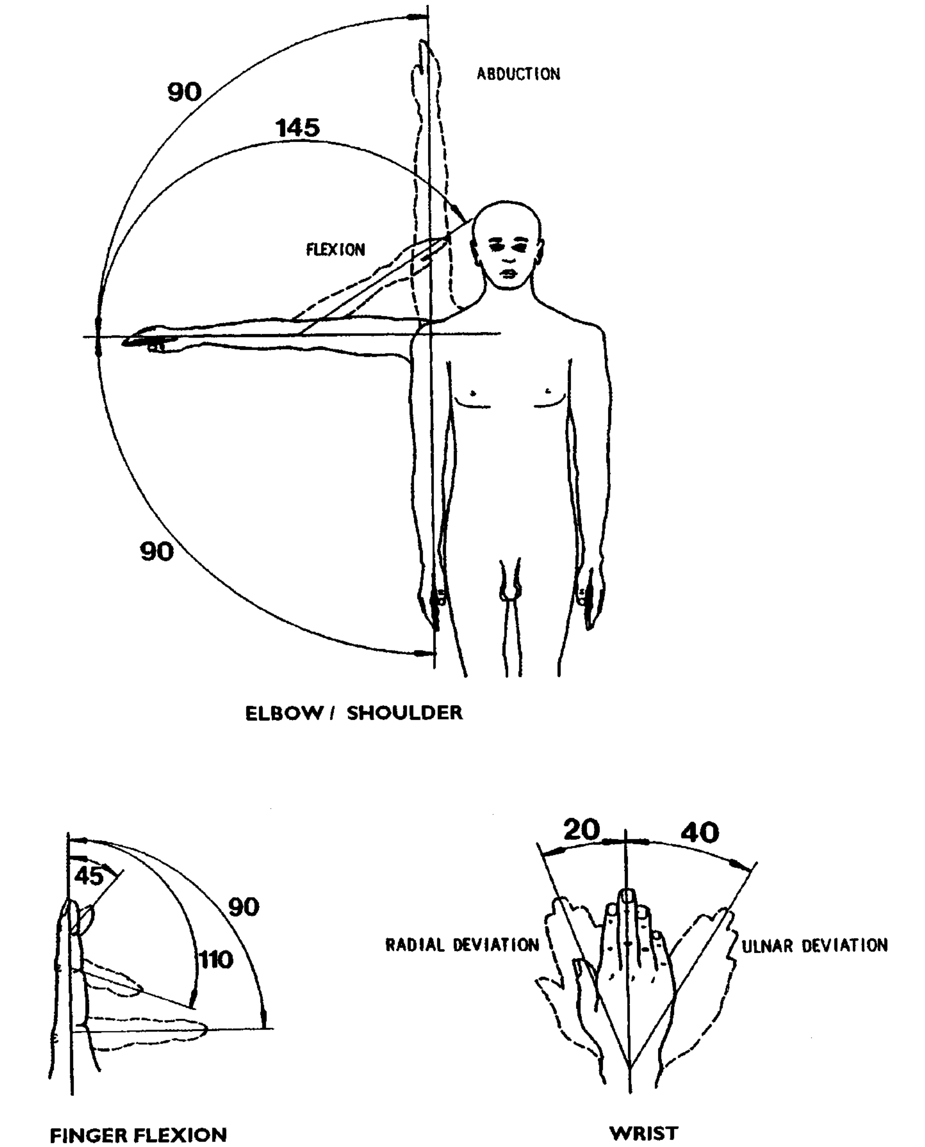
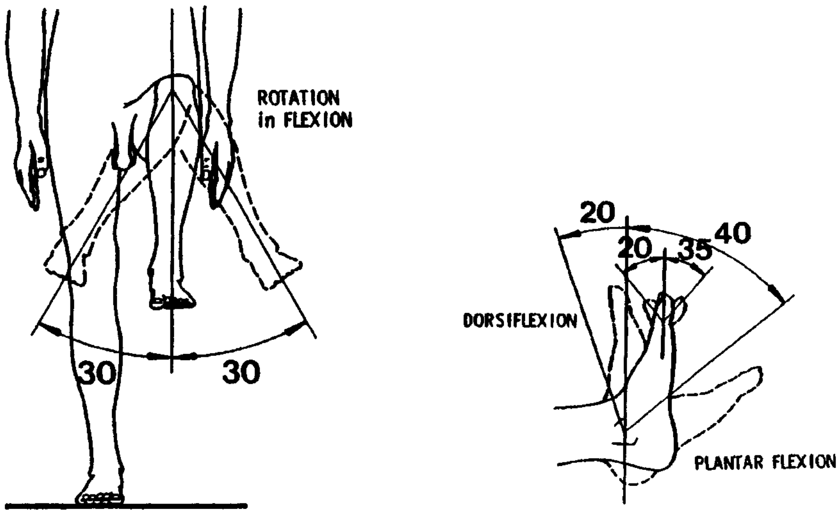


Fig. 15.2 (Continued).

of a product on its users. It also provides design guidelines in the form of constraints on the user interface. The various anatomical systems affect the level of anatomical analyses. In addition, the type of product being designed and the nature of the interaction between the user and the product determine what anatomical features need to be considered in the analysis. Such analysis is best when performed by someone trained in kinesiology (the study of human movement).

15.5.2 Biomechanical Analysis

Biomechanical analysis involves modeling the human body as a mechanical system. The various measurement tools used in biomechanical analysis all provide information about the mechanics of the user's body when interacting with a product or performing a task. Such analysis is appropriate when the goal is to quantitatively assess or validate the efficiency and/or safety of one or more



HIP ROTATION **ANKLE AND BIG TOE ROTATION**

Fig. 15.3 Selected examples of range of joint motions: lower extremities. (from B. G. Rutter, *Dynamic Anatomical Anthropometry.* ©1981. Reprinted by permission).

products. When precise measurements of the human interaction are required, a biomechanical analysis is essential. It provides quantitative measures of the patterns of muscular exertion and/or body position during actuation. This information provides an indication of the biomechanical efficiency and safety of the product tested.

Performing a biomechanical analysis using any of the four tools discussed below is a complex process requiring specialized equipment and personnel. Various other biomechanical tools exist. The following are the most commonly used.

Force Sensors

For this type of analysis, force sensors/transducers are mounted on a product or a test subject. Signals provide a sample force applied between the user and the test product. Such analysis allows researchers to develop a map of the distribution and range of forces involved in the use of a product. If loading is found to be too heavy in an area of the body that cannot handle such a load, designers know they must rework the concept design to ensure user comfort and safety.

Force Plates

These sensing devices provide feedback to researchers on a user's center of gravity and sway/motion during product interaction. Sensors takes sample measures of weights applied during different positions of user activity. These measures allow researchers to determine the activity's affect on a body in order to determine possible stress, strain, fatigue, and injury to the user.

Accelerometers

These devices measure the rate of movement change over time in order to determine user velocity during product use. Sensors sample the range of acceleration of different parts of the user's body in order to determine overall movement rates. Such data are critical in that it tells researchers how using different products affects users' movement (i.e., level of fatigue) over time.

Data Glove

This research tool has sensors that measure the movement of a user's hand and all related digits during product operation. The data collected allows researchers to track grip extents, various grip architects, grasping strategies, and the range of movement of the entire arm during product use. Researchers analyze this information to determine whether a product will cause overextension, thereby causing pain and injury.

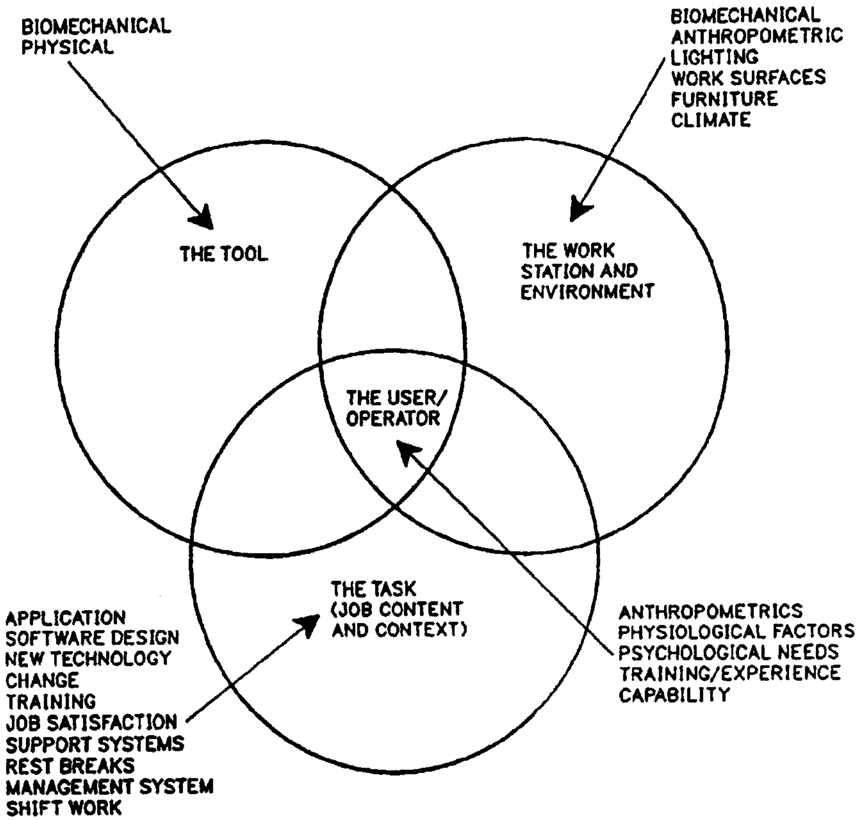


Fig. 15.4 Model of user interface issues: factors involved. (from Ref. 2. Reprinted by permission).

15.5.3 Task Analysis

Task analysis involves breaking a job function down into its constituent parts, assessing human resources and time requirements, then using the information to redesign the task to optimize user output. The systematic breakdown of the individual tasks into sub-tasks allows a thorough review and the subsequent improvement of a product or system. Task analysis has been applied to the assessment and redesign of products, industrial worksites, information displays, product control panels, architectural layouts, and so on. It is most effective in the review of multisequential and/or complicated activities.

15.5.4 Link Analysis

Link analysis is used to identify inefficiencies in time/motion paths of a user performing a task and details frequencies of such paths. Time/motion analysis traces can be performed directly on photographs of a task/product and can be recorded with a motion-detection system. Results graphically illustrate the human interface and allow for the identification of inefficiencies and repetitive motions that are nonproductive or may lead to diminished productivity or injury. Link analysis provides a graphic measure of the user interface and contributes a relatively quick yet precise evaluation of the path of human interaction with a product or system.

15.5.5 Motion Analysis

This assessment method determines the kinematics (measurements of the space/time attributes of human movement) of the user interface. Motion analysis provides a detailed quantitative profile of a movement required for a particular product-related activity. Such analysis provides a detailed quantitative assessment of a product's efficiency, consistency, and safety.

15.5.6 Thermographic Imprint Analysis

Thermographic imprints are used to analyze the physical interaction between a product and its user. For this study, a product or concept design is treated with a heat-sensitive paint system that changes color when in contact with heat from the user's body. The result is a visual thermographic imprint that illustrates patterns of contact between the user and product that are not readily available from photographs or videotape. This form of analysis is useful in diagnosing potential interface problems, such as excessive contact areas, accidental activation of controls, and pressure on sensitive anatomical features.

15.5.7 Low-Speed Cine Analysis

Low-speed cine analysis involves analyzing videotape frame by frame using an image capture system. This technique is especially useful for exploring the kinematics of tasks/interfaces that either occur very quickly or are too complicated to follow through normal observation. In addition, time/motion studies can be performed. This analysis provides a detailed quantitative analysis of human movement that can be used to assess the efficiency, consistency, and safety of the user interface.

15.6 DESIGN RESEARCH METHODS

Design research tools and techniques are often used in conjunction with various ergonomic analyses in order to optimize a product's usability. Both qualitative and quantitative tools are used to define user needs, product features and functionality, purchasing criteria, and end-user reactions to currently available products and new product concepts.

It is important to differentiate the following forms of analyses from traditional market research. Where methods of research such as focus groups serve to catalogue what customers do, design research goes one step further by analyzing why they respond as they do. Design research tools have the ability to move beyond more shallow, traditional market research and allow researchers to discern patterns in seemingly chaotic customer behavior.

15.6.1 Competitive Product Analysis

Competitive product analysis provides a systematic evaluation of competitive product performance, design, ergonomics, safety, comfort, and other similar design factors. It also provides comparative testing among products or product concepts to establish performance benchmarks and relative performance ratings. Resulting quantitative data include function and feature analysis, assessment of fit and finish, assessment of assembly, appropriateness of materials and support manuals, effectiveness of instruction guides, and statistical evaluations of the intuitiveness of controls and interface logic. Competitive product analysis can range from an internalized approach to a user-based treatise whose scope is determined by demographic guidelines.

The exploratory nature of this form of research dictates that it be executed early in the product development process. An abbreviated competitive product analysis with users can serve as a form of design validation after a product has been developed.

15.6.2 Product Performance Analysis

This form of design research involves the quantitative testing and evaluation of a product's performance attributes. Techniques include on-site and laboratory measures relative to use efficiency, product efficacy, and safety, using various types of sensing technologies. Depending upon the scope of inquiry and product/system being assessed, it may include motion analysis, biomechanical analysis, low-speed cine analysis, and so on. Quantitative data resulting from these analyses include such measurements as error rates, reaction and response times, motion-velocity analysis, acceleration, jerk, and movement paths of body parts. Qualitative evaluations, such as surveys, interviews, and observation, are also utilized.

Product performance analysis provides the clearest and most quantified and qualified measure in the process of existing product, competitive product, mock-ups, or prototype assessment. This design-research method can be used to establish industry benchmarks by ascertaining performance levels on a currently marketed product or in the concept development phase to assist in the selection of the optimal design.

15.6.3 Usability Studies

Usability studies provide both quantitative and qualitative information relative to the user's physical, cognitive, and perceptual relationship with the product. Test subjects are allowed to interact with the product for a period of time in the environment in which the product would normally be used. Researchers then interview users for a detailed understanding of the product's feature and functions, its ease of use, intuitiveness of operation, and so forth. Perceptual and actual responses are measured at various stages of product contact for an understanding of both the psychological and physiological interface.

15.7 COST–BENEFIT ANALYSIS OF ERGONOMICS AND DESIGN RESEARCH

Numerous industry studies have clearly illustrated positive cost–benefit advantages of implementing ergonomic programs. After all, what manufacturers cannot attest to some number of "No Problem Found" (NPF) returns of products? A buyer returns a product simply because it "does not work." Put simply, the product did not fit the user in some manner: perhaps it caused the user discomfort, perhaps he or she just could not figure out how to get the product to work, or perhaps the buyer thought the product was just too complicated or difficult to even try to use. In all of these scenarios, no fault can be found with the product or design except that it was developed without the user in mind.

Bear in mind that the cost of corrections to a poorly designed product geometrically increases throughout the development process. Therefore, human factors specialists should begin working with engineers and designers in the early stages of product development. When ergonomists are called in to fix a product that has already been sent to market and failed, costs will escalate.

A manufacturer's decision to adopt an ergonomic orientation will serve to reposition its products from a commodity-based supplier to a supplier of high-value products. Integrating ergonomics into a design program ensures more comfortable, safe, and productive design solutions and a better overall product for the end-user.

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