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DEVELOPMENT OF A METHOD FOR KINEMATIC ANALYSIS OF THE DOFFING PROCESS FOR A SPECIFIC GARMENT STYLE

by

Wendy Leiko Todd

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APPROVED:

Marjorie J. T. Norton, Chairman
Department of Clothing and Textiles

Ronald C. Bos
Department of Health and Physical Education

Jeffrey C. Woldstad
Department of Industrial Systems Engineering

Rinn M. Cloud
Department of Clothing and Textiles

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Blacksburg, Virginia

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Wendy Leiko Todd

Committee Chair: Marjorie J. Thompson Norton
Department of Clothing and Textiles

(ABSTRACT)

Garment doffing is recognized as an important element of safety, yet little information exists about doffing. The purpose of this research was to develop a method for kinematic analysis of the doffing process. The specific objectives were to 1) identify the basic critical movements involved in the doffing process of a selected garment style, 2) quantify the movement pattern. and 3) assess the validity of the method and the reliability of the data.

To study the movements involved in doffing a nightgown, doffings were recorded by video and WATSMART® (electro-optical) cameras. Relative angular displacement vs. time data were generated from video recordings using the Posture Taxonomy instrument, and from WATSMART recordings using a computer program. The movement experienced by the shoulder and elbow joints were close to the maximum physiologically possible. Twelve critical movements were identified using Roebuck's terminology.

The construct validity of the method was shown to be satisfactory by the convergence of the WATSMART and video position vs. time data. The reliability of the data was assessed in terms of intra- and inter-trial consistency. WATSMART was found to be sensitive enough to discern the differences in consistency due to garment style, subject fatigue and differing configurations of IREDs.

Based on the satisfactory convergence of the data and consistency of the data, it was concluded that using the WATSMART system to kinematically analyze the doffing

process was feasible. The degree of fidelity of the garments needs to be established before the method can be adopted for general use, however.

(249 words)

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CHAPTER ONE

INTRODUCTION

I. THE SCOPE OF THE DOFFING PROCESS

Garment doffing, the removal of a clothing item from the wearer's body, is an action performed by most human beings every day of their lives. This everyday activity has been recognized as an important element of psychological independence, convenience, and safety. Designers of clothing for the handicapped, children, and elderly consider the ability to undress and dress unaided a major need, both physiologically and psychologically (Hoffman, 1978; Horn, 1968; Rosenblad-Wallin, 1985; Watkins, 1984). Basketball players have used convenient "rip-off" type warm-up pants when quick substitutions are needed in game situations. Doffing is a common, positive response to clothing fires (Braun, Cobble, Helzer, Krasny, Peacock, & Stratton, 1976; Buchbinder, 1973; Lynn, 1970; Schramm, 1960), and the speed of doffing has been considered one of the determinants of garment flammability hazard (Norton, 1980; Solinger, 1988).

Designers of flight wear for military pilots have been concerned about doffing the parachute harness and armor assembly in water to prevent drowning of downed aircrew (Guill, 1989; Wormser, personal communication, July 1991), and doffing is cited as one of the critical mobility functions of pressure suits (Roebuck, Kroemer, & Thomson, 1975). Removal of clothing may prevent serious injury when working around heavy machinery where clothing may become entangled in moving parts (Knapp & Piercy, 1966). In chemical spills, removing contaminated clothing to avert contact with the skin can prevent injury (Fire, 1988; Watkins, 1984).

II. GARMENT DOFFING AS A CRITICAL SAFETY FUNCTION

Philo (1971, cited in Norton, 1980) defines hazard as "...a condition or changing set of conditions which, when combined with a human being in an unreasonable risk, can cause injury" (p.91-92). In some situations, doffing is a response to danger, for example, when a garment is ignited or splashed with a corrosive chemical. The speed with which a garment can be doffed is often tied to the impediments to doffing, such as difficulty in operating fastenings or lack of garment ease ("Industry Spokesmen", 1961; Norton, 1980). Doffing can be expedited by the incorporation of quick release fasteners in the garment, such as zippers, snaps, and hook-and-loop tape (Caddel, cited in Norton, 1980), though zippers may jam, which could hamper removal of clothing in an emergency ("Dressing Right", 1980). Some garments, however, must be closed systems for maximum safety, and fasteners can behave as punctures and so cannot always be used to make doffing easier (Watkins, Rosen, & Valla, 1978).

In the case of clothing fires, Buchbinder (1973) found the most common protective reactions were doffing, running, and beating flames with hands, and these reactions varied with the age and sex of the wearer and with the type of accident. Solinger (1988) proposed assigning a "flammability safety factor" to garments based on the wearer's ability to "...shed the garment unaided in sufficient time to avoid second and third degree burns when the fabric flames or chars at a given rate under standard atmospheric conditions and after contacting flame or hot ash for a given time" (p. 566). Lynn (1970) advised that "it might be better to concentrate on methods to remove burning garments from the body rather than on methods to render them fire retardant" (p. 9).

Johnson (1975, 1977), Kaeter (1980), Mikelson (1976), and Smith (1974) have promoted using doffing speed as the major design criterion for sleepwear as a means to reduce injury due to clothing fires. Johnson (1975) also advocated garment designs that opened fully down the front as opposed to those that opened only partially which force doffing over the head. Despite the recognized importance of doffing in hazardous

situations, no in-depth studies to date have been found which consider the physical motions involved in the doffing process.

III. THE LACK OF INFORMATION ABOUT THE DOFFING PROCESS

Recommendations have been made which advocate the consideration of doffing in the design process. Research has focused on the movement of body limbs underneath clothing only in so far as clothing affects the mobility of the limb, i.e., analyzing the movement of clothing as a covering over the limb which moves with the limb with some factor of impedance (Alexander, Garrett & Robinette, 1971; Bacharach, Egstrom, & Blackmun, 1975; Bolton & Simpson, 1971; Defence Research Establishment, 1985; Huck, 1988; Laubach & Alexander, 1975; Saul & Jaffe, 1955). In doffing, the movement of the clothing becomes a separate dynamic system from that of the limbs though controlled to some extent by the motion of the limbs. There is a need to develop a method which can analyze movement situations in which clothing is a non-mimetic system, such as doffing. If garments are designed to fit a clothing task, such as doffing, enabling the wearer to doff the garment without impediment to his mobility, higher levels of comfort and efficiency can result.

The purpose of this research is to develop and test a method for kinematic (motion describing) analysis of a garment doffing process. The specific objectives are to 1) identify the basic critical movements involved in the doffing process of a selected garment style, 2) quantify the movement pattern and 3) assess the validity of the method and the reliability of the data.

CHAPTER TWO

REVIEW OF LITERATURE

I. INTRODUCTION

The analysis of human movement is based on a number of different concepts and bodies of knowledge including anatomy and physiology, physics, and psychology. Kinesiology, the science of human movement, unites these different disciplines. In order to develop a method to study the doffing process, a kinesiological understanding of human movement is necessary. This chapter reviews the musculoskeletal basis of human movement, the behavioral and neurological aspects of controlling movement, the mechanical aspects of the movement itself, and the technological methods for acquiring movement data.

Also key to developing a method to study the doffing process is an understanding of design variables which affect the doffing process. Research exploring the effect of clothing on human movement and the doffing movement itself is also reviewed. Constructs from ergonomics and human factors engineering are explored to provide a conceptual basis for methodological development.

II. THE PHYSIOLOGY OF HUMAN MOVEMENT

The neuromusculoskeletal system is a dynamic, interactive system comprised of 206 bones, over 600 muscles, and a complex network of connective tissue and nerves. Ligaments connect bones to each other, forming joints, and tendons connect muscles to bones and across joints. Muscles are usually arranged in agonist-antagonist pairs across joints. Movement is possible when either or both muscles of a pair contract, creating torque about the joint. These contractions are stimulated by innervation of motor neurons via electrochemical energy. It is believed that the movement impulses may originate in

the cerebellum or the basal ganglia, and are refined by the cerebral cortex after initiation (Astrand & Rodahl, 1988).

II-1. JOINT MOVEMENT

Joint movement can be classified into three types of articulations: 1) diarthoidal or synovial (freely movable), 2) synarthoidal or fibrous (immovable), and 3) amphiarthoidal or cartilaginous (slightly movable). All joints of the limbs belong to the diarthoidal class of articulations. In these joints, the connecting bony surfaces are covered with articular cartilage. The joint capsule is comprised of an encapsulating ligament lined with synovial membrane which secretes synovial fluid, a lubricant, to facilitate movement without friction. Diarthoidal articulations can be subdivided into six groups:

1) Arthoidal - a gliding joint with limited movement, as in the carpals of the wrist;

2) Condyloidal - an ellipsoidal joint with movement in two planes without rotation, as of the ulna and radius at the wrist;

3) Enarthoidial - a ball-and-socket type joint which permits movement in all planes, and also rotation in the shoulder and hip joints;

4) Ginglymus - a hinge joint which permits a wide range of movement in one direction, as in the elbow;

5) Reciprocal reception - a saddle joint which prohibits rotation but allows movement in all planes, as in the thumb;

6) Trochiodal - a pivot joint which permits a twisting movement about a long axis, as in the forearm.

(Thompson, 1989)

The capability of a joint to move, that is, its **mobility**, is affected by the physical composition of the joint (fibrous tissue, cartilage, or synovial membrane), the shape of the bones it connects, the bulk of intervening soft tissues, the tension of ligaments and antagonist muscles, and the length of muscles. These properties are in turn influenced by the age, gender, and physical condition of the human (Chaffin & Andersson, 1984).

Physical condition can be temporarily modified by fatigue, i.e., fatigue can negatively affect mobility. Additionally, the articulation of some joints may prevent or hinder the articulation of another joint (e.g., an extended knee joint hinders flexion of the hip joint). Joint movement can also be artificially restricted by garments. Bulkiness, weight, poor fit, surface characteristics, and garment configuration have all been attributed with reducing mobility.

The range of motion is a measure of the mobility of a joint as expressed in angular displacement of limbs from a reference position. Table 1 contains the average range of motion for the 5th to 95th percentiles of college age men and women (specific age ranges were not available). According to the table, females have a greater range of motion than males, and 95th percentile subjects, greater than 5th percentile. Some joints, such as the shoulder, exhibit the ability to move in many directions (referred to as degrees of freedom) and possess a high range of motion in these directions. Range of motion usually refers to the maximum and minimum positions assumed by the body or its limbs during any one motion, and is defined in terms of the joint, its direction, and angular displacement (e.g., Figure 1).

III. THE PSYCHOLOGY OF HUMAN MOVEMENT

Motor learning is "a set of processes associated with practice or experience leading to relatively permanent changes in the capability for responding" (Schmidt, 1988, p. 346). As motor skills are learned, a task can be accomplished with less and less physical and mental effort, probably because movements are performed more efficiently or because information is processed more efficiently (Schmidt, 1988), however the reasons for the increase in efficiency of information processing are still unknown.

A component of motor learning is the feedback provided by the proprioceptors (also referred to as kinesthetic receptors), which are somatic sensory organs stimulated by the movement itself and which act as a mechanical guidance system, coordinating the efforts of the muscles to accomplish the desired movement. Astrand and Rodahl (1988)

TABLE 1

Link Range of Motion

JOINT	MOVEMENT	5th PERCENTILE FEMALE	5th PERCENTILE MALE	50th PERCENTILE FEMALE	50th PERCENTILE MALE	95th PERCENTILE FEMALE	95th PERCENTILE MALE	DIFFERENCE* FEMALE > MALE
Neck	Ventral Flexion	34.0	25.0	51.5	43.0	69.0	60.0	+ 8.5
	Dorsal Flexion	47.5	38.0	70.5	56.5	93.5	74.0	+14.0
	Right Rotation	67.0	56.0	81.0	74.0	95.0	85.0	+ 7.0
	Left Rotation	64.0	67.5	77.0	77.0	90.0	85.0	NS
Shoulder	Flexion	169.5	161.0	184.5	178.0	199.5	193.5	+ 6.5
	Extension	47.0	41.5	66.0	57.5	85.0	76.0	+ 8.5
	Adduction	37.5	36.0	52.5	50.5	67.5	63.0	NS
	Abduction	106.0	106.0	122.5	123.5	139.0	140.0	NS
	Medial Rotation	94.0	68.5	110.5	95.0	127.0	114.0	+15.5
	Lateral Rotation	19.5	16.0	37.0	31.5	54.5	46.0	+ 5.5
Elbow	Flexion	135.5	122.5	148.0	138.0	160.5	150.0	+10.0
Forearm	Supination	87.0	86.0	108.5	107.5	130.0	135.0	NS
	Pronation	63.0	42.5	81.0	65.0	99.0	86.5	+16.0
Wrist	Extension	56.5	47.0	72.0	62.0	87.5	76.0	+10.0
	Flexion	53.5	50.5	71.5	67.5	89.5	85.0	+ 4.0
	Adduction	16.5	14.0	26.5	22.0	36.5	30.0	+ 4.5
	Abduction	19.0	22.0	28.0	30.5	37.0	40.0	- 2.5
Hip	Flexion	103.0	95.0	125.0	109.5	147.0	130.0	+15.5
	Adduction	27.0	15.5	38.5	26.0	50.0	39.0	+12.5
	Abduction	47.0	38.0	66.0	59.0	85.0	81.0	+ 7.0
	Medial Rotation (Prone)	30.5	30.0	44.5	46.0	58.5	62.5	NS
	Lateral Rotation (Prone)	29.0	21.5	45.5	33.0	62.0	46.0	+12.5
	Medial Rotation (Sitting)	20.5	18.0	32.0	28.0	43.5	43.0	+ 4.0
	Lateral Rotation (Sitting)	20.5	18.0	33.0	26.5	45.5	37.0	+ 6.5
Knee	Flexion (Standing)	99.5	87.0	113.5	103.5	127.5	122.0	+10.0
	Flexion (Prone)	116.0	99.5	130.0	117.0	144.0	130.0	+13.0
	Medial Rotation	18.5	14.5	31.5	23.0	44.5	35.0	+ 8.5
	Lateral Rotation	28.5	21.0	43.5	33.5	58.5	48.0	+10.0
Ankle	Flexion	13.0	18.0	23.0	29.0	33.0	34.0	- 6.0
	Extension	30.5	21.0	41.0	35.5	51.5	51.5	+ 5.5
	Adduction	13.0	15.0	23.5	25.0	34.0	38.0	NS
	Abduction	11.5	11.0	24.0	19.0	36.5	30.0	+ 5.0

*Listed are only differences at the 50th percentile, and if significant ($\alpha < 0.5$)

Note. From Posture Taxonomy (p. 14) by Bob Malone, 1991, Master's thesis, Virginia Polytechnic Institute and State University. Reprinted by permission.

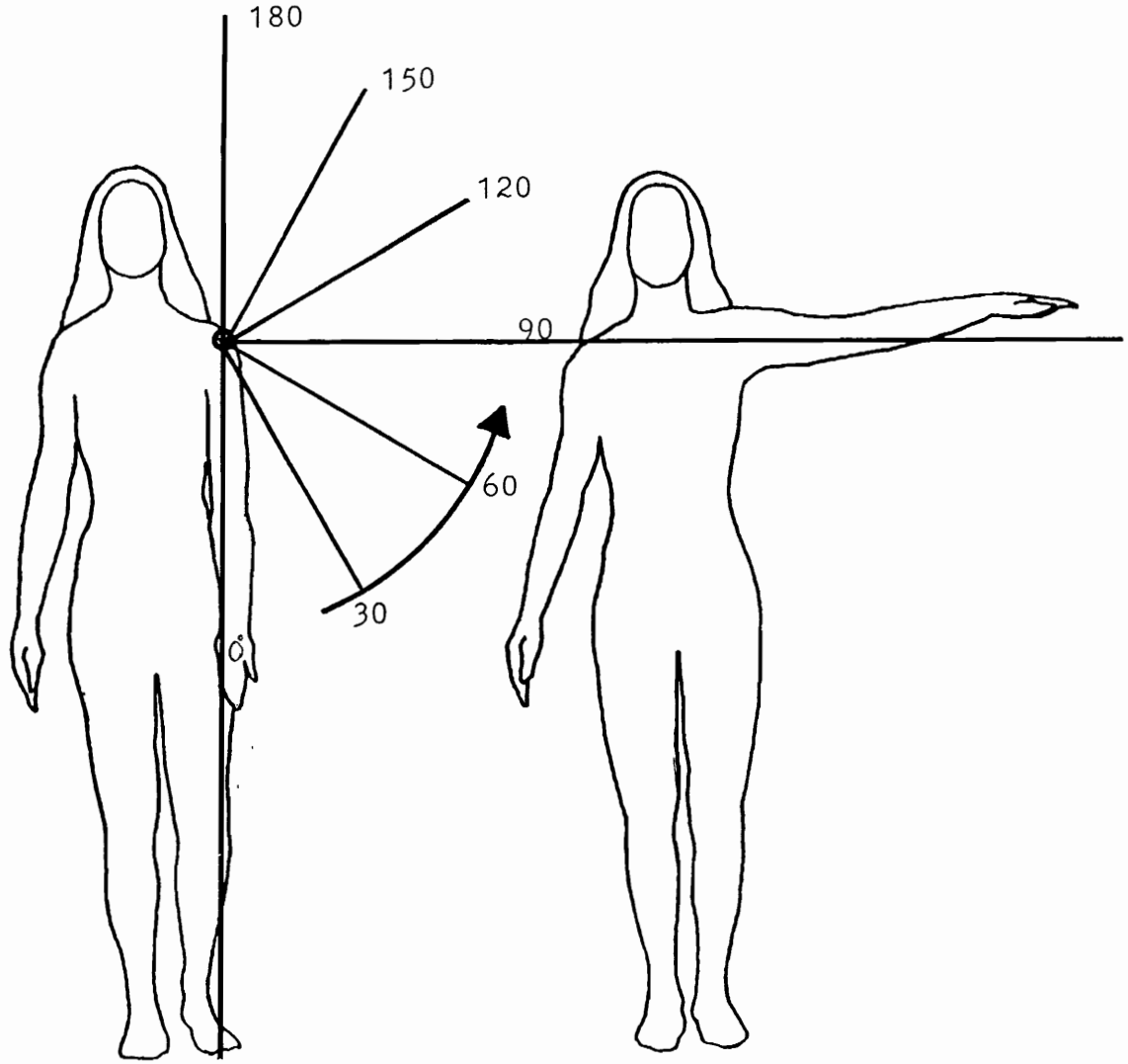

Figure 1
Example of Range of Motion

speculated that "an integration of central programs and the feedback loops from proprioceptors are probably responsible for periodicity and modulation of motoneural activity [coordination]" (p. 109). The nervous system uses proprioceptive information (such as muscle tension, muscle length, change of velocity in muscle length, joint angle, joint movement, head position, skin stretch, and contact with surfaces) to modify and adjust muscular function so that voluntary movements can occur subconsciously (Gowitzke & Milner, 1988). This information is somehow integrated with the expectations or past experience of what movement is desired, and modifications are made to muscle activity to conform to this expectation (Gowitzke & Milner, 1988). A result of practicing is movement pattern consistency, and can be measured by various kinematic analyses, e.g., position vs. time (Schmidt, 1988).

IV. THE MECHANICS OF HUMAN MOVEMENT

The mechanics of human movement are concerned with applying the physical laws of classical mechanics to the study of the body moving through time and space. Movement of any kind can be approached from two different mechanical points of view: kinematic or kinetic. The kinematic approach provides a description of the movement without regard for the causes or consequences of that motion. For example, one may determine the time needed to accomplish the motion, the position of the body during the motion (in linear or angular terms), or position vs. time (velocity, acceleration). A kinetic analysis addresses the causes for the states of motion of an object. This review concentrates on the kinematic analysis of movement, which is most relevant to this research.

According to Barham (1974), the three measurable mechanical quantities in human movement are the body in motion (matter), the distance or angle through which the body travels (space), and the duration of the movement (time). The distance traveled by the body is referred to as displacement, and is a vector quantity (i.e., has both magnitude and direction). The measurement of angular displacement is based on the geometry of the

circle. The body (or portion of it) is represented by the radius of a circle. As the body changes position, it rotates the radius along the circumference of the circle. The portion of 360 degrees circumscribed by the radius gives the angular displacement.

IV-1. BIOMECHANICAL MODELS

Kinematic analyses rely on geometric biomechanical models to represent the human body. Geometric biomechanical models simplify the body and focus attention on the macro-level moving parts, thereby facilitating the study of motion to yield useful information. Mathematical modelling of the human body makes possible the use of computer graphics, a display tool in biomechanical analysis (Delp & Delp, 1989). The various models which have been proposed can be classified into segmented rigid body models and link models. Reynolds (1978) concluded that "...the concept of a body segment is useful in describing mass distribution; the concept of a body link is used when describing body motion" (p. IV-8).

IV-1.1 Link Models of the Human Body

Link models are based on the skeletal structure of the human body. In these models the human body is simplified to a collection of mechanical linkages (Dempster, 1955). The body is divided into line segments, namely the head, shoulders, upper arms, lower arms, hands, hips, thighs, calves, and feet. Chaffin and Andersson (1984) describe how the anatomical reality of skeletal muscular linkages is simplified into a link model:

> "the measurement of the length of various body segments in a linkage system assumes that the segments are connected at easily identifiable joint centers...identification of segment joints for the limbs can be difficult, because the bony landmarks are often covered by muscle and fat tissue, especially at the shoulder and hip joints...[on living subjects] it is possible to project approximate centers-of-rotation by moving the adjacent body segments through the range of motion of the joint. The intersection of the long axis center-line of the segments during such movements defines the joint's approximate center-of-rotation...link lengths can be defined as the distance between projected centers. These link lengths have been correlated with distances measured between palpable bony landmarks located near the joint centers-of-rotation of interest" (p. 53-54).

Several link models of the musculoskeletal system have been developed to study various reactions of the human body such as stress analyses of bone, calculation of ligament and muscle forces across joints, and the kinematics and kinetics of locomotion (King, 1984). Most biomechanical models combine kinetic and kinematic aspects of movement (e.g., calculation of forces and torques due to acceleration of a limb). Range of motion analyses are most easily performed by modelling major body segments as single links between major joint centers. Figure 2 is an example of one link model.

Link models are used to calculate the range of motion by representing limbs of the body as a series of line segments (links) and joint centers as single points in space. The long axes of the limbs are represented by line segments, while palpable bony landmarks represent joint centers. When either or both of the line segments connected by a single point in space change position, the angle subtended by the two line segments represents the angular displacement or the range of motion. Points comprising the ends of these segments can be assigned Cartesian or polar coordinates once an origin is defined, and their positions and displacement in space can be derived mathematically. Thus, the range of motion is a calculated quantity based on approximation rather than being a real quantity.

A problem with approximating joint centers of rotation with palpable bony landmarks is that bony landmarks are manifested on the surface of the body while joint centers exist inside the body. Such an approximation results in the same kind of error that approximating the center of a sphere with a point on the surface produces. It might be fair to say that no defensible general statement on accuracy of the range of motion can be made, since the range of motion is based on a mathematical abstraction of the body

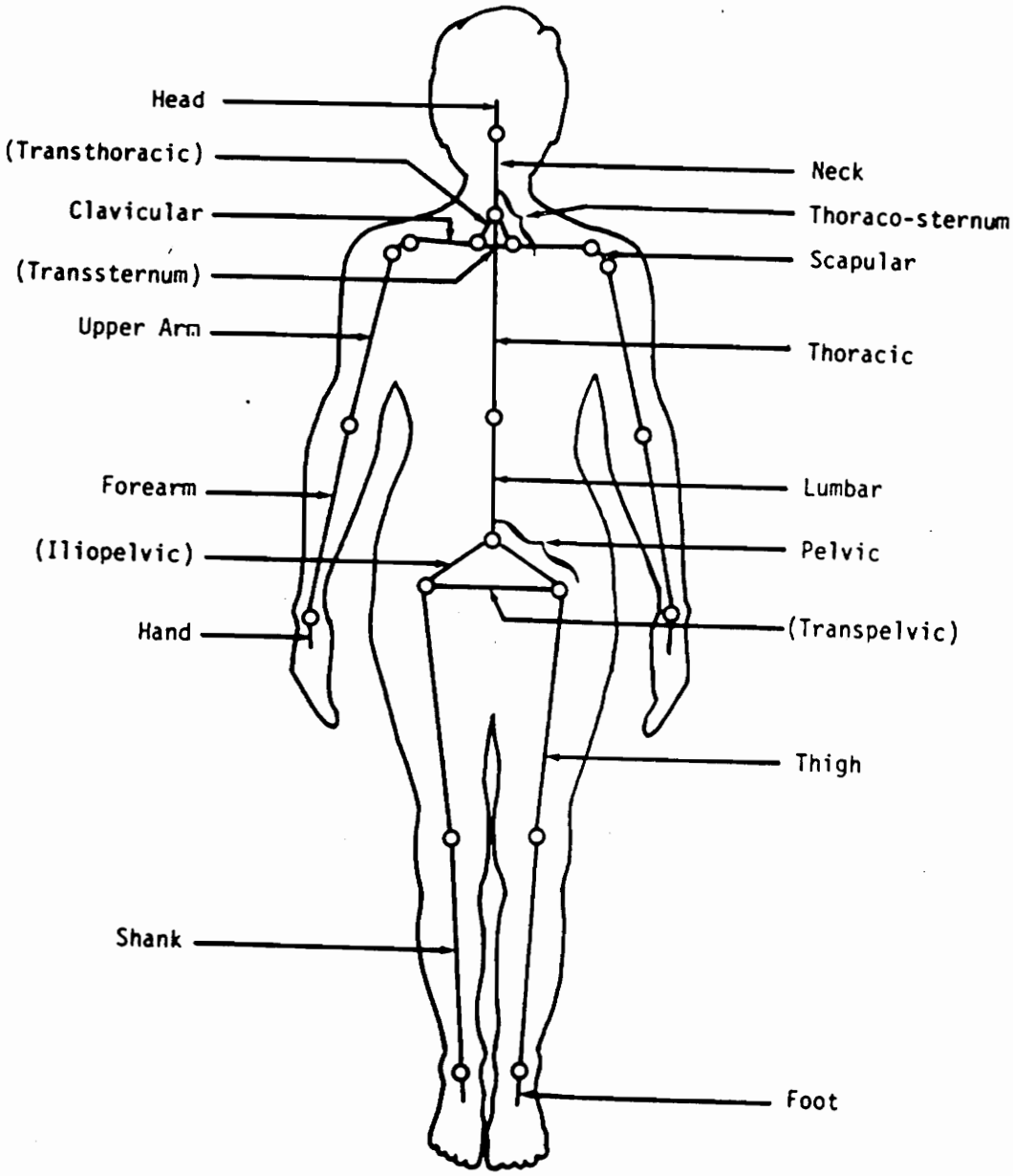

Figure 2

Link Model of the Human Body
(Webb Associates, 1978)

(the joint center of rotation) which is poorly (but necessarily) approximated by surface landmarks.

V. QUALITATIVE METHODS FOR MOTION ANALYSES

Three common types of qualitative analysis of human motion are nominal analyses, evaluative analyses, and symbolic analyses. Nominal analyses identify discrete motions using a rigidly defined taxonomy. Evaluative analyses assign a particular value to each discrete motion (e.g., the comparator terms used in judging an athletic event). As the objective of the present study is identification and quantification, evaluative analysis will not be reviewed here. Symbolic analyses are notation systems which attempt to record the movement using various pictorial/symbolic representations of movement or posture.

V-1. CRITERIA FOR NOTATION SYSTEMS

There appears to be no readily available source of notational theory, however criteria for evaluating or devising a system can be found in the literature and may serve as a conceptual base. The conceptual base for recording movement with pen and paper relies on the abilities of the recorder to translate three- dimensional movements into a written mode.

Karhu, Kansi, and Kuorinka (1977) cited simplicity and lack of ambiguity as the main criteria for a notational system. Corlett, Madeley, and Manenica (1979) contended that ease and speed of recording were primary considerations. Priel (1974) discussed the information processing difficulties of representing movement with pictures wherein perception of depth is lost, and of representing movement with words wherein the visual component is missing. Malone (1991) pursued the information processing approach and concluded from his development of a posture targeting method that notation systems which employ 1) a realistic pictorial representation of the human form, 2) spatial matching between the pictorial representation and the actual posture observed, and 3) comparative rather than absolute judgments are desirable from a perceptual and cognitive standpoint. Comparative judgments are defined by Sanders and McCormick (1987) as

those based on comparison of two or more stimuli (e.g., the AATCC Gray Scale for Color Change, which presents gradations in contrast) whereas absolute judgments rest only on a comparison held in memory (e.g., grading the quality of a single specimen of wool without quality samples).

Guest (1984) provided the most complete list of criteria in the literature reviewed for devising a movement notation system:

1) universality (should cover every form of movement, e.g., dance, sports, work,etc.)

2) comprehensiveness (cover every aspect of the movement to the degree of detail required for the recording purpose)

3) anatomical accuracy

4) veracity (capturing the intent of the true movement)

5) logicality (overall consistency in presentation of the concepts underlying the system, and simplicity in general structure)

6) visuality (arrangements of signs should provide visual patterns through which movements can be sightread)

7) legibility

8) practicability (economical in appearance, instruction, redundancy, and amount of writing; unambiguous, versatile, compatible with computer use)

Guest also discussed the modes in which movement notation can be described: anatomically, spatially, directionally, and in terms of the path.

V-2. NOMINAL ANALYSIS OF JOINT AND SEGMENTAL MOVEMENTS

Medical or kinesiological terminology has been traditionally used to describe movement. The space in which human movement occurs has been described in terms of three cardinal axes and planes (Figure 3). The body is divided into top and bottom halves

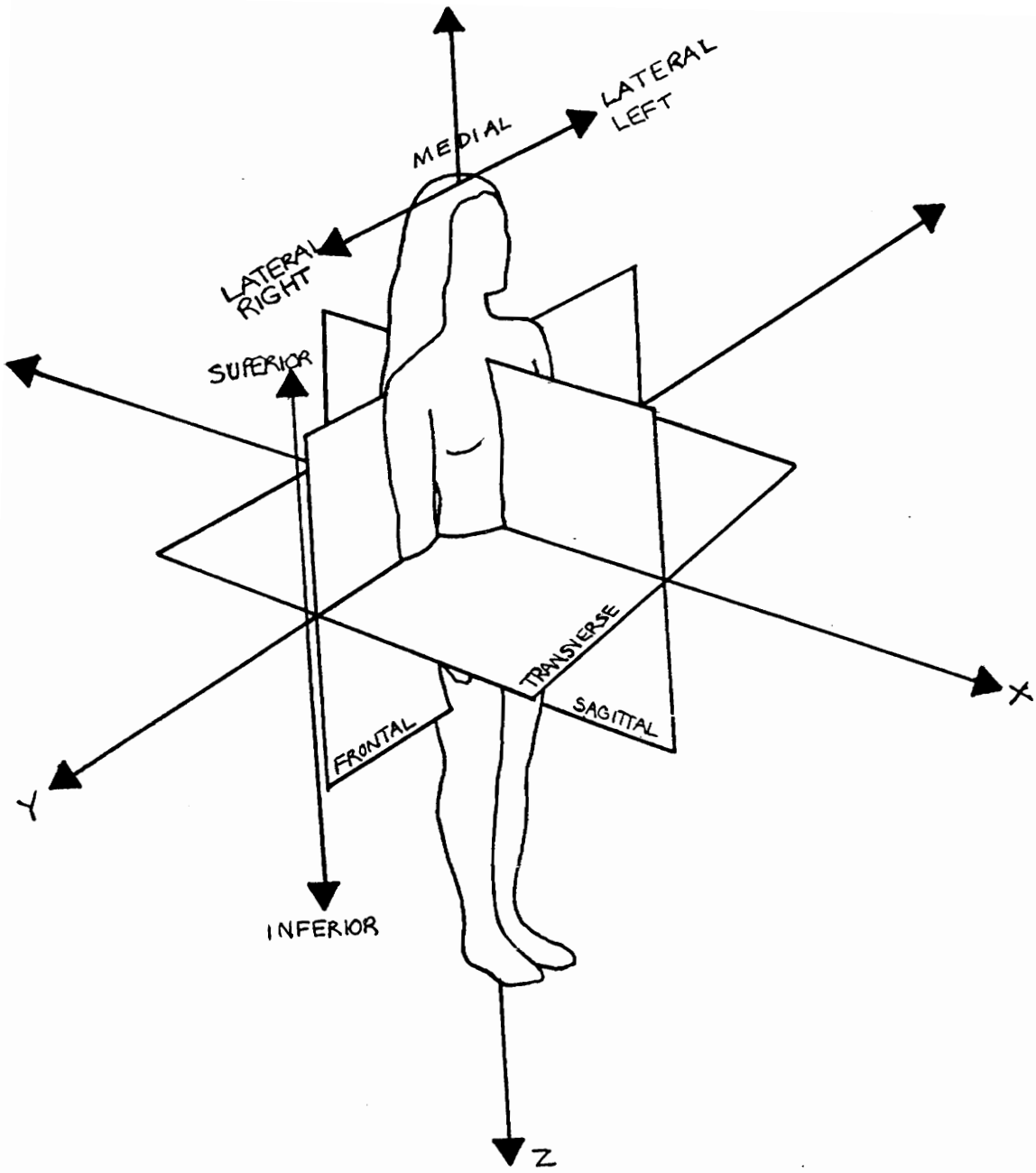

Figure 3

Cardinal Axes and Planes

at the pelvic line by the transverse plane along the X-axis; into left and right halves by the sagittal plane along the Y-axis which runs through the vertical center of the body; and into front and back halves by the frontal plane along the Z-axis (there is no set location of this plane although it is convenient to locate it through the hole of the ear).

Direction is also indicated by the terms medial, which refers to aspects of limbs or their movements toward the midline of the body, and lateral, which refers to aspects of limbs or their movements from the midline of the body. The terms distal and proximal indicate the reference orientation of the limb, the former referring to the end of the limb furthest from the midline of the body, and the latter to the end of the limb closest to the midline of the body. These terms are sometimes combined with movement terms, such as flexion and extension, to describe a movement more completely.

Appendix A presents a glossary of the traditional terms and their interpretations. Engineering terms are sometimes used in place of the more traditional terms but are not uniformly used by all researchers, creating considerable confusion in the literature (Kroemer, 1986). For example, the term "sagittal plane" is sometimes replaced with "XZ plane" or "lateral plane" or "horizontal plane". Roebuck (1968) listed other problems with the traditional system of notation:

1. Traditional terminology is based on Latin and Greek roots whose original definitions are not precise enough to describe the complex nature of human motion.

2. Movements which continue beyond the plane of reference are then moving in the opposite direction of the original definition.

3. Terms do not strongly and clearly define in which plane the movement is taking place.

4. Terminology is difficult to pronounce and memorize.

Priel (1974) criticized traditional terminology as providing no help in defining the position of the limbs in space because the terms are limited to describing the activity of the

muscles and the direction of the movement. Roebuck (1968) developed his own terminology which has since been recommended by other researchers (Chaffin & Andersson, 1984; Kroemer, 1984; Watkins, 1984). Roebuck combined abbreviations of the traditional names of the planes in which a movement occurs with suffixes representing the direction of the movement, to produce new root words indicating the type of movement.

V-3. SYMBOLIC ANALYSIS OF JOINT AND SEGMENTAL MOVEMENT

Symbolic forms of motion notation have been developed as well. Dance notation is probably the earliest and most well developed type of movement notation, and can be used for dynamic as well as static analyses. Guest (1984) presented an exhaustive compilation of dance notation systems developed in the western world including Feuillet, Stepanov, Nijinsky, Nikolais, Morris, Sutton, and Eschkol-Wachman. Perhaps more well known are the systems developed by Laban and by Benesh. Laban's (1975) system, called "Labanotation", has been applied to many fields. It codes movement both temporally and spatially using an integration of geometric shapes, shading, and symbols on a vertical staff which represents the human body. Benesh notation (cited in Guest, 1984) records changes in body position on a 5-line horizontal staff using shorthand signs. The stave represents the two-dimensional aspect of the body, while the shorthand signs represent position. Despite the adaptability of these systems to a number of non-dance fields, Corlett, Madeley, and Manenica (1979) criticized the Benesh and Laban systems as too time consuming to learn to be useful for widespread use.

Fields other than dance have also developed notation systems. Birdwhistell (1970), a sociologist, combined stick figures with alphanumerics to result in "kinegraphs", abbreviated notations that can describe static positions in temporal, anatomical terms and spatial terms which denote their communication function.

Ergonomists have also developed methods for subjectively analyzing static positions of the human performer. Job postural evaluation methods are used in ergonomic assessment of tasks. Priel (1974) proposed a system that would allow definition of

postures from repeated observation, where the levels at which joints and limbs were located and the direction and the degree of movement would be recorded on a "posturegram". The posturegram represents the body pictorially in the transverse, frontal, and sagittal planes; the recorder records in angular degrees his observations of the posture. Karhu, Kansi, and Kuroinka (1977) developed the OWAS system for identifying unhealthy postures. Schematics of common postures are coded numerically, and classed as postures of the lower limbs, upper limbs, and back. Thus an overall picture of the posture can be indicated numerically by combining schematics from each of several classes.

Kember (1976) adapted Benesh notation to analysis of sitting postures. Corlett, Madeley, and Manenica (1984) developed the Posture Targeting method in which the analyst records the angular positions of the limbs by placing a small X on each of the postural targets. The radial lines of the target represent angular displacement in the transverse plane, while the concentric circles represent rotation from the vertical axis in the sagittal plane. Corlett et al. reported "high consistency" in recordings of static postures. Malone (1991) developed the Posture Taxonomy (PT) method to record static postures. This method combines realistic diagrams of the human form in all three planes with a 360-degree target to estimate angular displacement of limbs from the reference position. A representation of the limb of interest is depicted at 15-degree intervals about the target. Malone concluded that the PT method was moderately accurate for recording static postures.

VI. OBJECTIVE QUANTITATIVE METHODS FOR MOTION ANALYSES

In this section, some common words have been assigned very specific meanings. **Sensor** refers to the instrument which seeks energy signals from anything in its field. A camera is a common type of sensor, while a more exotic example is a thermal scanner. **Object** is the general term which refers to whatever serves as a source of energy signals for the sensor. This can be a person, a building, a tree, etc., or can be an energy -

emitting marker affixed to one of these. **Subject** is the specification of the object as the human being whose movements are under study.

VI-1. CLASSIFICATION OF OBJECTIVE METHODS

There are several objective methods available for describing human posture in quantitative terms. These can be classed as **direct** and **indirect**. Direct methods are those in which contact with the subject is required to collect data, and the indirect are those which require no contact. Krag (1985) listed the following practical aspects to be considered in the application of any of these methods:

1) level of disruption of normal functioning of the subject

2) accuracy of measurement technique

3) thoroughness of measurement technique (e.g.,two-dimensional vs. three-dimensional)

4) convenience of data acquisition

5) convenience in data processing

6) overall cost

(p. 86)

Several of the direct and indirect methods developed to date are reviewed below; the discussion encompasses historical perspective as well as the practical aspects listed above. Table 2 summarizes the discussion of the practical aspects (except accuracy) for each type of method, and is based on current literature. Comparator terms (low, moderate, high) are used to indicate the qualitative level of the properties addressed; these have been assigned according to the subjective assessment of the investigator based on the literature. While accuracy results for each will be indicated in the text, it is important to keep in mind that there appears to be no standard way to measure accuracy. Some researchers chose to measure the consistency between repeated trials (correlations); others chose to measure the consistency of the measurement (standard deviations). Not only the type of statistic varies but also the units, from degrees to millimeters, and even the data on which the figures are

TABLE 2

Comparison of Motion Analysis Techniques

Technique	Level of Disruption	Ease of Data Acquisition	Amount of Data Reduction	Relative Cost
DIRECT				
Simple goniometer	high	very poor	low	very low
Elgon	high	poor	low	low
Flexometer	high	poor	low	low
INDIRECT				
Photography	very low	moderate	moderate	low
Cinematography (*using digitizer)	very low	good	moderate	moderate
*Close range Photogrammetry	moderate	good	high	high
*Electro-optical	low	very good	high	high
*Acoustic	moderate	very good	high	unknown
*Laser	very low	very good	high	unknown

*computerized

based differ (vs. two-dimensional). As mentioned previously, this review concentrates on those kinematic methods which yield positional data.

VI-2. DIRECT METHODS

Goniometry (derived from "gonia", meaning angle) is the measurement of angular joint motion. From the reviewed literature, goniometry appears to be the only direct method for obtaining range of motion data. A frequently used instrument is the simple or universal goniometer, basically a 360-degree protractor with a movable pointer attached to a movable arm. The axis of the goniometer is aligned with the stationary limb, and the movable arm with the moving limb, thus static postures must be assumed. Data acquisition is very simple and inexpensive, but is susceptible to errors in measurement due to soft tissue movement over joint centers as well as to operator error in positioning the goniometer. Cole (1971) reported that for trained specialists the accuracy averaged about $\pm$ 3 - 5 degrees. A simple goniometer is relatively inexpensive at about $25.00 (Lafayette Instrument Catalog, 1990-91).

Leighton (1955) developed the flexometer to reduce errors associated with shifting joint centers. In this type of goniometer, the movements of the dial and pointer are controlled by gravity and operate independently of one another. The device is strapped to the joint of interest and a direct reading gives the range of motion in angular degrees. Laubach (1978) and Chaffin and Andersson (1984) describe the construction and mechanics of the device in more detail. The flexometer is still prone to error if the device shifts because of muscular contraction, and measurements are limited to planar flexions and extensions though a static posture need not be assumed throughout. Leighton (1955) reported a high reliability with correlation coefficients in the .90's. The flexometer is more expensive than the simple goniometer at about $500.00 (Lafayette Instrument Catalog, 1990-1991).

The electrogoniometer, or elgon, came into use in the 1960s and is a more precise version of the simple goniometer using a potentiometer (variable resistor) to measure limb

displacement. The device used to be defined as an "exoskeleton linkage system" strapped with tape or gauze to the joint of interest while an electronic transducer converted the physical movement to an electrical signal. Currently, the bulky exoskeletons of 20 years ago have been replaced with small devices similar in size to conventional goniometers. The signal is converted to angular degrees by an analog-to-digital converter; thus there is more data processing than in the techniques discussed above. Adrian, Tipton, and Karpovich (1965) cited an average accuracy of $\pm$ 1-2 degrees for the exoskeleton type of elgon. A digital version of the electrogoniometer costs about $525.00 (Lafayette Instrument Catalog, 1990-91), and a computerized version including software runs at about $700.00 (Lafayette Instrument Catalog, 1990-91).

Other instruments employing the goniometric method include the rubber band goniometer (Neukomm, 1974), the electromechanical goniometer (Schoenmarklin & Marras, 1989/1990), and the three-dimensional goniometer (Lamoreux, 1971). Although goniometric techniques are widely used today, some serious problems are that 1) most are limited to planar, or two-dimensional, movement analysis, 2) only one or two joints can be instrumented at a time because of the relative bulkiness of the devices resulting in very slow data acquisition, 3) only frozen postures may be measured, 4) the attachment of the devices may disrupt normal movement patterns, and 5) calibration, mounting, and aligning can be tedious.

Direct methods can be used in conjunction with live subjects, mannequins, or film images. Watson (1984) used **model simulation**, a technique in which a live model was positioned beside a screen displaying a single frame of the activity. The model then simulated the movement on the screen and joint angles were measured using some kind of goniometer.

VI-3. INDIRECT METHODS

Five different methods are reviewed below and are divided into two-dimensional and three-dimensional techniques.

VI-3.1 Two-Dimensional Techniques

These techniques are limited to planar (x,y) movement analysis, i.e., only one view of the subject may be studied and analyzed at a time. All the techniques reviewed in this section use a two-dimensional image of the subject for analysis.

VI-3.1.1 Still Photography

Photographic techniques are unique in that absolutely no physical impediment is placed on the subject in order to collect data. Subjects can perform without the attachment of any apparatus, and thus the most natural performance can occur. Another advantage is that data acquisition can take place virtually anywhere a camera can be placed (Miller & Petak, 1973).

One of the earliest examples of photographic analysis of movement was provided by Muybridge (1925). He studied the gait of quadruped animals by photographing their locomotion frame-by-frame from the sagittal view. Bresler and Frankel (1952) adapted still photography to acquire range of motion data as follows: the movement was filmed, usually from a sagittal view; then the angles formed by the joints were measured with a protractor by the experimenter who approximated joint centers and limb axes from the film images. Dempster (1955) used multiple exposures to record the minimum and maximum positions of the joint range. While data acquisition is relatively easy, it is slow and prone to errors inherent in film media (Smith, 1976):

1) film blurriness which may cause inaccurate sighting of markers,

2) shifting of markers due to muscular contraction,

3) inaccurate assumptions of body dimensions (e.g., those not visible because of obscuring by other body parts, or those projecting back in space),

4) parallax, or photographic perspective error,

5) possible altering of genuine information through smoothing or cleaning data that are "noisy" due to the above problems, and

6) introducing further error through mathematical approximation.

Noss (1967) and Plagenhoef (1968) developed mathematical techniques to reduce the error due to parallax, but Miller and Petak (1973) commented that the resulting angles could be considered only rough approximations. The cost of photographic techniques is directly related to the degree of resolution (thus accuracy) desired; more sophisticated equipment yields more clearly identifiable boundaries. Today a typical single lens reflex camera setup with strober would cost about $800 (Ewald-Clark, 1991).

VI-3.1.2 Cinematography

The advent of cinematography (moving pictures) in research soon made the use of single frame cameras obsolete. The simplest analysis that can be employed is segmental analysis described by Northrip, Logan, and McKinney (1974):

1. Observe the total performance several times to gain a general impression of the movements involved in the execution.

2. Film the performance under "gamelike conditions".

3. Show the projected image frame-by-frame on a screen and trace the movement of limbs, specific landmarks, and/or joints.

The technique was improved by placing subject surface markers on joint centers (e.g., ink-spots, reflective tape), and by refining the filming process (e.g., stroboscopy, rotating-slit shutters). Frame-by-frame manual planar digitizing combined with computer technology yielded positional data by collection of (x,y) coordinates as identified by the surface markers (Northrip, Logan, & McKinney, 1974). A refinement on digitizing, the Vanguard Motion Analyzer uses a movable array of diagonal crosshairs which can be lined up with the axis of the limbs on either side of the joint and the angle between the lines measured (Watson, 1984).

While more accurate than the subjective approximation of joint centers in photographic methods, digitizing is prone to human error in positioning the digitizing

device and it is time consuming and expensive. The digitized points must be converted to angular data by trigonometric equations, but this can be done easily and quickly with a computer program. Markers that are obscured can be approximated using prediction equations based on mathematical biomechanical models. Data acquisition is more tedious than with photographic techniques because cine techniques require manual planar digitizing with an (x,y) reader (digitizer), and data processing is required to convert (x,y) points to angular degrees although use of a computer reduces operator effort. A typical cinematographic motion analysis system costs about $12,300 (Lafayette Instrument Catalog, 1990-91), and there are additional costs of film processing which for 16mm film is quite expensive compared to still photography or video tape.

The errors in still photography listed above (Smith, 1976) also apply to cine techniques. Smith noted that three-dimensional techniques are necessary to minimize errors due to parallax, data smoothing, and mathematical approximation. Additionally, two-dimensional techniques can only record movements occurring in one plane (x,y), a severely limiting factor in kinematic studies, while three-dimensional techniques can be used to identify nonplanar (x,y,z) movements in space.

VI- 3.2. Three-Dimensional Techniques

There are various three-dimensional techniques, but most can be characterized as **photogrammetric**. Photogrammetry was originally applied to topographic mapping, and has been adapted to defining the shape of almost any object. Ghosh (1988) defined photogrammetry as "...the art, science and technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of recorded radiant electromagnetic energy" (p.1). Wolf (1974) defined it as the systematic recognition and identification of objects using data from sensing instruments such as infrared sensors, radar, and thermal scanners. Karara (1989) expanded the above definition to include information acquired by x-rays, electron microscopes, and photodiode arrays with analog or digital outputs.

Systems which use digital data acquisition are referred to as digital or on-line photogrammetric systems (Karara, 1989). Mikhail (1989) states that "...the primary characteristic of photogrammetry as a metrology technique is that the measurements are carried out indirectly" (p. 7). One of the earliest photogrammetric applications was that of Laussedat (cited in Torlegard, 1980) who used terrestrial photographs taken with metric cameras to create maps.

VI-3.2.1. Photogrammetric Theory

According to Mikhail (1989), the primary function of photogrammetry is to geometrically reconstruct a three-dimensional object from two or more different perspective projections, which is the basic concept of human stereoscopic vision (Figure 4). Such a reconstruction in space will yield its spatial location and is dependent on transforming the signals collected by the various sensors to points in space. Atkinson (1989) separates this reconstruction into two phases: a) acquiring the data from the object to be measured, or **data acquisition,** and b) reducing perspective projections (two dimensions) into orthogonal projections (three dimensions), or **data reduction.** The difference between perspective and orthogonal projections is that in the latter the scale is constant throughout the projection, while in the former the scale changes from point to point. Accurate data cannot be taken from a perspective projection because of the fluctuation in scale; the difference in scale must be rectified by data reduction.

One data reduction technique is the **direct linear transformation** (DLT) method which yields the location of a point with coordinates from a set of two-dimensional image coordinates according to the following equations:

$$(b_1X+b_2\ Y+b_3Z+b_4)-x(b_9\ X+b_{10}Y+b_{11}Z+1)=0$$
$$(b_5X+b_6\ Y+b_7Z+b_8)-y(b_9\ X+b_{10}Y+b_{11}Z+1)=0$$

where (X,Y,Z) are the object's calculated coordinates, (x,y) are the measured image coordinates, and the b_i's are the 11 DLT parameters to be determined. The b_i parameters are calibration constants determined from the reference system of known coordinates;

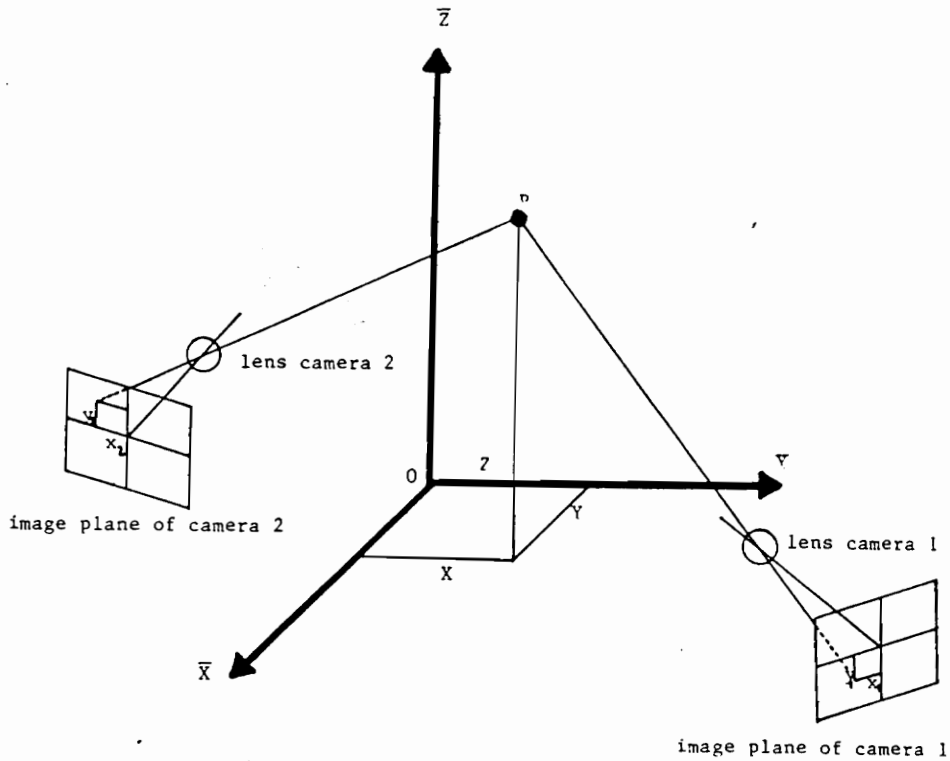

Figure 4

Geometric Relationships of Photogrammetric Theory

once these have been determined, the above equations are solved for the unknown spatial (X,Y,Z) coordinates of the object. The (x,y) image coordinates are obtained from standard film analysis techniques. Lens distortion is corrected by calibration of an array of reference points against the image positions observed by the camera. Purswell (1990) explained the principle behind DLT:

> "...the intersection of lines from different cameras' perspective centers to the object locates the depth of the object. In general, these rays from the cameras to the object will not intersect exactly. Hence, an error vector which connects the two rays can be defined. The 'true' position of the object is taken to be the midpoint of this vector." (p. 6)

Abdel-Aziz and Karara (1971, cited in Miller & Petak, 1973; Woltring & Marsolais, 1980) originally developed the DLT method for applications in still photography. Martin and Pongratz (1974), Marzan and Karara (1975, cited in Miller, Shapiro, & McLaughlin, 1980) and Shapiro (1978) adapted the DLT method for use in high speed cinematographic techniques. Miller, Shapiro, and McLaughlin (1980) refined the method to estimate the errors associated with calculation of the parameters.

VI-3.2.2. Close-Range Photogrammetry

Close-range photogrammetry (also known as nontopographic) refers to applications outside topographic mapping (Karara, 1989) where the object to sensor distance is limited to under 300m (Torlegard, 1980). In its early stage of development, close-range photogrammetry was applied to deriving body volumes and surface areas (Hertzberg, Dupertuis, & Emanuel, 1957; and as cited in same: Leydolph, 1954; Miskin, 1956; Zeller, 1936). Ayoub, Ayoub, and Ramsey (1970), Bullock and Harley (1972), and Lippert, Hussain, and Veress (1974) were among the first to apply close-range photogrammetric techniques to measuring human motion. Chao and Morrey (1978) applied these methods to roentographic analysis of joint rotation in the elbow. As in two-dimensional techniques, there has been a progression from photography to multiple

camera cinematography. Bergemann (1974), Huntington, Kendall, and Tietjens (1979), Miller and Petak (1973) and Van Gheluwe (1974,1975) were early experimenters in cine techniques.

A problem with early close-range photogrammetric techniques was that external camera parameters (orientation, position) had to be known. Metric cameras, those in which the interior orientation is constant and in which fiducial (orthogonal) marks are included in the picture plane, met this requirement. Nonmetric cameras could be used if the cameras were positioned so that their optical axes intersected at a common point, but required cumbersome measurements of external camera orientation involving theolodites, spirit bobs, and other paraphernalia. Abdel-Aziz and Karara (1971) developed the direct linear transformation (DLT) method which allowed nonmetric cameras to be used by numerically rectifying the image plane with the object plane. Van Gheluwe (1978) refined the DLT method to allow arbitrary positioning of cameras by filming a steel reference frame (six tubes fitted together orthogonally) in the optical field of two arbitrarily placed cameras. This defined triaxial coordinate system allowed backcalculation of the camera position and orientation. Van Gheluwe (1978) reported a mean accuracy of $\pm$ 1mm for reconstruction of linear distances; for reconstruction of motion coordinates, Lippert et al. (1974) achieved standard errors of $\pm$ 0.12 mm and $\pm$ 0.05 degrees.

Chao (1978) assessed the limitations of photogrammetric systems:

1. The film data must be manually decoded, which can be quite time consuming and prone to error.

2. Use of two cameras requires additional care in maintaining alignments and additional time in film-data reduction.

3. If still cameras are used, reference points cluster together when the sampling rate is low, causing difficulty in maintaining synchronization of the reference points.

4. Reference points can be obscured from the camera by other body segments.

5. Additional calculations that may produce cumulative errors are required to estimate relative motions.

(p. 402-403)

The close-range photogrammetric system using metric cameras has been described as "costly" (Ayoub et al., 1970). Data processing is fairly sophisticated, but use of computers makes it more a matter of time than effort. Data acquisition with an (x,y) digitizer (as required by these systems) can be quite time consuming as well as prone to operator error.

Electro-optical systems. These systems are also referred to in the literature as optoelectronic, photodiode, videographic, "nontraditional", and motion-tracking. These systems employ an electro-optical, or "matrix", camera which has as its image plane a grid of photodetectors. Most systems employ some type of marker on the object/subject that can be detected and tracked by these special cameras. A common type of marker is a diode which emits light of some kind. A source of some confusion is how the word diode is used. A diode is defined as any electronic device through which current can pass in only one direction; thus, photodetectors are a type of diode and markers are also a type a diode. For clarity, the term photodetector will be used instead of diode to indicate the sensing mechanism of the camera. Another source of confusion is that the literature sometimes refers to markers in the general case as LEDs, but in this discussion, "diode" will be used to refer to the general case of any marker emitting energy, and "light emitting diode" (LED) will refer to diodes which emit visible light energy.

Inherent in electro-optical systems is the assumption that energy from the marker can be approximated as a single point in space (Kehl, 1986). The accuracy of the determined location of the diode is dependent upon how small the diode is perceived to be by the sensing equipment; a diode perceived to be "large" results in uncertainty about its exact location (Fisher, 1989). Signals from diodes attached to the subject are converted into analog electrical voltages, which are in turn converted to digital form to provide a two-dimensional intensity grid. Using this grid, points in space can be derived by

computer using some type of data reduction method. An example of an electro-optical system is the WATSMART by Northern Digital, Inc. Data acquisition and processing are relatively fast through use of automatic data gathering by computers.

Charged coupled device (CCD) cameras are another type of optical hardware used to detect and track markers. These systems employ a linear silicon photodetector divided into 2048 pixels. Light is emitted from a diode and impinges on the photodetector. The pixel which receives the most light determines the location of the light emission. Because this system determines the location of the light source from a single pixel, rather than by using an averaging technique to locate the center of a light emission (which is prone to error because reflections can pull the average off center), CCD types of systems can improve accuracy to 0.1mm (Fisher, 1989) rendering them particularly suitable for high frequency movements, such as finger or lip movement.

The system for transmitting the signal from the subject may be **active**, meaning that the marker "generates" its own energy and transmits it to the sensor, or **passive**, meaning that the marker "borrows" energy provided by an external source to transmit to the sensor. Active systems often require wiring connections between the marker and a power source while passive do not. The choice of an active or passive system rests on the kind of motion being measured and the required level of accuracy.

Active systems using infrared emissions can allow each diode to be "individualized" by assigning it a unique strobing frequency. WATSMART is an example of an active system using infrared emitting diodes (IREDs). LEDs have been used in other systems but the signal cannot be individualized, though Schendel and Patterson (1986) achieved an accuracy level of $\pm$ 2 degrees using LEDs. Infrared light diodes have several advantages over visible (LED) light diodes: a faster flashing rate, smaller size, and radiation exclusively in the infrared spectrum (Woltring, 1984) which is both not distracting to the subject and less "polluted" by ambient light sources, so the signal is purer and the data more accurate. WATSMART yields a reported accuracy of $\pm$ 1.5mm for reconstruction of

points, but the accuracy level relies heavily on the minimization of IR reflection (Kehl, 1986). Electro-optical systems are fairly expensive, ranging from $50,000 to $125,000 (Kehl, 1991).

Some applications of active electro-optical systems to the study of human movement include: Stramler (1985) who applied the system to the determination of functional arm reach envelopes; Van Gheluwe and Hebbelinck (1985) and Van Gheluwe, Ruysscher, and Craenhals (1987) to the study of the tennis serve; and Woltring and Marsolais (1980) to gait analysis. A videographic system using LEDs was employed by Schendel and Patterson (1986) to automatically obtain range of motion measurements.

Passive systems often use reflective tape as markers. Such systems allow unimpeded movement but are susceptible to distraction of the subject because of the required strobe light source directed at the subject, signal "dulling" due to ambient light sources, and difficulty in uniquely identifying each marker on the subject. Pearcy, Gill, Hindle, and Johnson (1987) reported problems with maintaining the markers in the field of view and with cross-over interference between signals, however use of retroreflective markers (e.g., reflective tape) coupled with strobe lights alleviated these problems. Another passive system, ExpertTrak^{TM}, achieved a mean accuracy of $\pm$ 1.5mm for reconstructed points without the use of strobe lights (Koff, 1990).

A problem common to both active and passive systems is attaching markers to the subject. Double-sided tape has been used frequently, but in the case of strenuous exertion both sweat and the protrusion of bony prominences may loosen the adhesive bond between skin and marker. In active systems, the subject may become "hung up" in the wires which may contaminate the movement. Samuelson, Wangenheim, and Wos (1987) addressed these problems by development of a special coverall with sewn-in markers, and reported good results in a variety of movements. However, use of such a coverall is not appropriate for all situations, such as in field studies and in doffing. In the case where the subject must wear his own clothing, markers must then be attached to the surface of

the clothing, a potential source of error due to mislocating joint centers under shifting fabric. Further, movement may be disguised by bunched clothing.

Non-optical systems. Krag (1985) reports that acoustic systems have been used in position detection applications. UNOPAR, developed by Goldman and Nadler (1956) as cited in Roebuck, Kroemer, and Thomson (1975), uses the Doppler effect to estimate changes in location of an audio emitter strapped to the limb of interest. Hsiao and Keyserling (1990) developed an ultrasonic system for posture measurement, but the system was limited to static postures with a reported standard deviation of $\pm$ 1 cm between the standard coordinates and the measured coordinates. An, Jacobsen, Berglund, and Chao (1988) developed a magnetic tracking device for studying rigid body motion, but did not apply the system to a human subject. Sorenson, Starr, Yang, and Donath (1986) have evaluated a laser-scanning system for studying human motion and achieved an accuracy of $\pm$ 2mm and $\pm$ 0.5 degrees.

VII. APPLICATION OF HUMAN FACTORS DESIGN PRINCIPLES TO GARMENTS TO ENHANCE DOFFING CAPABILITY

Human factors are those elements which influence the efficiency with which people can use equipment to accomplish the functions of that equipment (Meister, 1971). These elements include the macro- and microenvironments with which humans interact. Ergonomics has been defined as "fitting the work to the person" (Chaffin & Andersson, 1984), by considering the interaction of humans and their working environment.

Comfort is an important factor which is modified by the environment. Comfort has been defined as the state of mind and body in which there is physiological, physical, and psychological balance between the wearer, his clothing, and the environment (Sweeney & Branson, 1990). As the definition implies, comfort is a very broad concept comprised of many factors. Comfort is often measured in terms of the thermal balance of the wearer (Hollies & Goldman, 1977), but it also encompasses nonthermal factors, such as ease of fit to the complexly curved surfaces of the body (Fourt & Hollies, 1970).

Clulow (1983) referred to comfort as the ability of the clothed body to move without restriction. One of the most important influences on this type of comfort is fit. Fit has been defined as the relationship between body size and shape and garment size and shape (Shishoo, 1990). There are two approaches to fitting a garment to the human: functional and structural (Berry, 1970, cited in Heisey, Brown, & Johnson, 1988). Functional (also known as dynamic) fit is that which spatially accommodates the motion and activities of the body, while structural (also known as static) fit is that which accommodates only the dimensions and configuration of the static body. Structural and functional fit in clothing design can be viewed as the analogs to classical and functional anthropometry in workspace design.

Anthropometry is the science of measuring the human body. Classical anthropometric methods involve taking static measurements of the human body in standard positions. Functional anthropometric methods collect data on the human body in the dynamic positions assumed to perform a task. Efficiency is defined as the performance of a function in the least wasteful manner. Efficiency can be enhanced by application of functional anthropometric data to design of the worker's environment. A typical functional measurement is **arm reach**, the distance the human must extend his arm to grasp a control; it encompasses the whole reach envelope of the arm and is a function of mobility (Sanders & McCormick, 1987). Another common measurement is **workspace**, the space of the physical macroenvironment surrounding the worker (Sanders & McCormick, 1987). The boundary surfaces, and so the spatial volume, for any specific task are those which permit the performance of the relevant operations. The reach envelope is influenced by the posture of the human, the movements to be performed, and the workspace. Application of functional anthropometric data to design of a workspace results in a macroenvironment in which the worker's efficiency is optimized by considering the task in the design of the workspace dimensions. "The reasonable limits of

such space are determined by functional arm reach..." (Sanders & McCormick, 1987, p. 341).

Just as efficiency is optimized by designing the workspace (macroenvironment) to fit a work task, efficiency is also maximized in clothing by designing the garment (microenvironment) to fit a movement task. The performance of a task while wearing clothing is directly affected by the mobility possible in the clothing (Roebuck, Kroemer, & Thomson, 1975; Sanders & McCormick, 1987). Watkins (1984) stated that clothing is related to comfort and function in that:

> "...if an individual can move in a garment without straining it, the individual is generally more comfortable. If people don't have to work against their clothing, they can perform more effectively" (p. 144)

Logically, this relationship can be extrapolated to include the performance of clothing tasks. If garments are designed to fit a clothing task, such as doffing, enabling the wearer to doff the garment without impediment to his mobility (measured by range of motion), higher levels of comfort and efficiency will result.

VIII. HUMAN MOBILITY AND DOFFING CAPABILITY

Several researchers have advocated using mobility as a clothing design criterion (Alexander, Garrett & Robinette, 1971; Hollies & Goldman, 1977; Roebuck, Kroemer, & Thomson, 1975; Rosenblad-Wallin, 1985; Watkins. 1984). Mobility is so critical a function in chemical protective clothing that a standard, ASTM F-1154 (1988) entitled "Standard Practice for Qualitatively Evaluating the Comfort, Fit, Function and Integrity of Chemical Protective Suit Ensembles", has been developed. Some studies on the effect of clothing on mobility are reviewed below. Garment configuration and construction, and fabric properties are variables to be considered in mobility studies, and encompass such properties as bulk, weight, constriction, friction, and stretch. It seems, however, that very few researchers have designed studies in which these are treated as manipulated

independent variables. Most studies compared garments against each other with the aim of identifying the one which allows more mobility, without seeking to identify the fabric/garment characteristics which made it so.

VIII-1. RESEARCH ON THE EFFECT OF CLOTHING ON MOBILITY

The degree of movement performance has been used in several studies as a measure of clothing effects on mobility. Range of motion movements possible in various garment configurations are among the most common addressed in the literature. Gregoire, Call, Omlie, and Spicuzza (1985) analyzed 12 range of motion movements to determine the restriction to aircrew mobility resulting from wearing various chemical-biological warfare protective garments. A similar study was performed on the Apollo 16 spacesuit ("Apollo 16 Spacesuit," 1951). Bacharach, Egstrom, and Blackmon (1975) compared the mobility in two different diving ensembles to that possible in a simple swim suit using 14 functional postures. Eight range of motion movements were measured by Huck (1988) to evaluate the mobility of fire fighters in three styles of turnout gear.

Other types of movements have been used to quantify the restriction on mobility due to clothing. The study of Saul and Jaffe in 1955 (cited in Atkin, 1980; Huck, 1988; Watkins, 1984) timed clothed subjects who ran a slalom course as fast as they could; the time needed to run the course was used as a measure of gross motor performance. Saul and Jaffe concluded that performance decreased as more clothing was worn. Laubach and Alexander (1975) used functional arm reach capability to assess the effect of personal protective equipment of U.S. Air Force pilots. They compared the reach possible in a minimum flying assembly ("shirt-sleeve") with a maximum flying assembly (winter) and concluded that the range of motion was significantly greater in the minimum flying assembly. Prevatt (1991) evaluated the fit of limited-use protective coveralls by analyzing subjects' perceptions of the mobility possible in the various coverall styles while executing seven exercises. Other studies which also found a reduction in range of motion associated with various clothing configurations include that of Brown (1954, cited in Mullet, 1991)

and that of Nicoloff (1957, cited in Adams & Keyserling, 1991), both of whom evaluated the effect of clothing on the use of the arm and shoulder.

VIII-1.1 The Effect of Garment Configuration on Mobility

Several studies investigated the effect of specific garment configurations on mobility. Alexander, Robinette, and Garrett (1971), using observational techniques, concluded that a pressure suit must be designed with joints that coincide with the body joints of the subject in order to "...permit maximum efficiency of these anatomical hinges" (p. 389). Atkin (1980) used a fully articulating mannequin to recreate filmed body positions of wheelchair bound people. A closely fitted garment was placed on the mannequin, and the garment slashed at each articulation point. The openings or overlaps that occurred were traced and their shapes incorporated back into the garment for more mobility. Watkins (1984) discussed the "hobbling effect" which "...occurs when any two body segments are tied together in some way or when the bulk of the clothing makes separate limb movement difficult" (p. 170). Garment designs, such as styles in which the linear distance from joint to joint is reduced (such as in dolman or kimono sleeves, or in dropped crotches), were identified by Watkins as producing the hobbling effect.

VIII-2. THE EFFECT OF FABRIC PROPERTIES ON MOBILITY

Studies directly addressing this issue appear to be rare. The only one found thus far is that of Adams and Keyserling (1991) who conducted a preliminary study on the effect of weight on arm movement. Garment weight as a variable was isolated by constructing weight sets equivalent in mass and distribution to two garment configurations. Subjects performed a reciprocal touching task and a cranking task wearing each garment type, then wearing each weight set (without garments). Adams and Keyserling found that garment weight may increase movement time and reduce arm movement efficiency, but not significantly for short duration tasks. They speculated that for tasks of longer duration, the effect of weight on gross arm movement would be greater due to fatigue.

More information about the effect of specific fabric properties on mobility can be gleaned from speculations by researchers who attempted to explain the differences in mobility of different garment types. For example, Huck (1988) attributed the loss of mobility suffered when wearing a self contained breathing apparatus to the bulk and weight of the apparatus, and to the "restrictive" nature of the webbed straps. Bacharach et al. (1975) noted that the Mark XII diving suit was more flexible dry than wet, which might imply a change in weight due to water retention, or a change in the frictional properties of the skin or fabric due to wetting. Fabric-to-fabric or fabric-to-skin frictional resistance and fabric flexibility (the ease with which excess fabric can be contracted) are fabric variables Watkins (1984) associated with the hobbling effect.

Some research has been done to address the effect of fabric on fit, which is an important component of mobility. Bolton and Simpson (1971) examined the fabric extensibility required to construct a close-fitting pressure suit. Kirk and Ibrahim (1966) examined the effect of fabric extensibility on fit as well. They developed a method called "anthropometric kinematics" in which the linear change in skin dimension over a flexed joint was compared to the dimensional change in fabric dimension. They summarized this relationship by the following simple formula: Body Skin Strain = Garment Fit + Garment Slip + Fabric Stretch. However, this relationship appears to be conceptual rather than analytical.

Fourt and Hollies (1970), in their discussion of comfort related to fit, listed several fabric properties important to secure good fit: surface finish and character, flexibility and drape, shear and buckling properties, and seam characteristics.

VIII-3. TREATMENT OF DOFFING IN RESEARCH

To date, there has been little research focused on doffing. The existing research has centered on the overall speed of doffing, or on the ease of doffing perceived by the wearer, or on the frequency of doffing as a response to clothing fires. While designers of clothing for the handicapped, children, and elderly consider the ability to undress and

dress unaided a major need, both physiologically and psychologically (Hoffman, 1978; Horn, 1968; Rosenblad-Wallin, 1985; Watkins, 1984; Wingate, Kaiser, & Freeman, 1986), it seems that no intensive work has been done to address this need by relating doffing to variables of the garment, fabric, or wearer. Rather, ease of doffing has been treated as a post-hoc criterion for garment evaluation; with a few exceptions, doffing has usually been measured subjectively by a posttest questionnaire in comparative terms (easy, difficult, etc). As a garment design criterion, ease of doffing has been given minor treatment as one of several goals for the garment. When prototype garments have been designed with ease of doffing in mind, the emphasis has been on fastening systems.

The subjective evaluation of doffing by wearers is most often done by response to a questionnaire. Roebuck et al. (1975), in their proposed model for development of a garment prototype, placed fit and mobility testing of the completed prototype at the end of the evaluation cycle which is also in accordance with ASTM F-1154-88. Atkin (1980), Auffart (1983), and Hoffman (1978) included "ease of doffing" on a questionnaire for subject evaluation of prototypes.

Exceptions to evaluation of doffing by questionnaire can be found in clothing flammability literature. Caddel (cited in Norton, 1980) and Norton, Johnson, and Jordan (1984) employed doffing as an evaluative criterion in terms of the time needed to doff the garment compared to the speed of burning; the former to that of fabric specimens, the latter to that of garments. Buchbinder (1974) took an epidemiological approach in examining the frequency of doffing as a protective response in clothing fire situations. A Canadian military project determined the areas of maximum stress in a garment during donning and doffing (Defence Research Establishment, 1985).

The information provided by post-hoc evaluation and general knowledge of garments has been applied to recommend improvements in garment design to facilitate doffing. The recommendations have usually been concerned with clothing for the elderly, disabled, and children (Atkin, 1980; Forbes, 1971; Hoffman, 1978; Reich, 1986; Watkins,

1980). Fastening systems (e.g., Velcro , snaps), design of component pieces (e.g., raglan versus set-in sleeves), and alteration techniques (e.g., incorporating more room in seams or pattern pieces) are some of these recommendations. There have been many proponents of using ease of doffing as a design criterion. Solinger (1988) proposed a mandatory flammability index based on ease to doff, which would require apparel designers to consider doffing as a design criterion. Johnson (1975, 1977), Kaeter (1980), Mikelson (1976), and Smith (1974) have likewise promoted it as a design criterion through their involvement in product liability cases regarding clothing fires. Roebuck et al. (1975) specified the doffing activity as a critical mobility function of a pressure suit. For doffing to be a design criterion, it is necessary to know what discrete movements comprise it as well as the qualitative and quantitative components of these movements, but no prior research is known to have addressed the identification of these movements.

VIII-4. VARIABLES AFFECTING THE DOFFING PROCESS

The same variables which affect mobility can also be assumed to affect a specific mobility task, such as doffing. As reviewed previously, physiological variables include the age, sex, and physical condition of the wearer, and concurrent articulations of other joints; physical variables include garment and fabric properties. There is a paucity of research which addresses the effect of specific garment and fabric variables on doffing; with a few exceptions, most of the information is speculative in nature.

One exception is work at the University of Minnesota (cited by Norton, 1980) which addressed the design of clothing for quick removal. Design features which made clothing more quickly removable included easily operated fastenings, full-front garment openings, and large armscyes and sleeve openings. Caddel (1977-78, cited in Norton, 1980) also found that more tight-fitting garments were more difficult to remove than loose-fitting ones.

To recapitulate from the literature reviewed, the garment and fabric variables associated with restricting mobility include fabric weight, bulk, extensibility, moisture

content, surface finish and character, flexibility and drape, shear and buckling properties, and garment characteristics, such as fastening systems and sleeve designs. Since these variables are interrelated with one another, it is obvious that treatment of each as an isolated variable can be a difficult task.

IX. SUMMARY OF THE REVIEW OF LITERATURE

The analysis of the human movement is based on a number of different concepts and bodies of knowledge including the musculoskeletal basis of human movement, the behavioral and neurological aspects of controlling movement, the mechanical aspects of the movement itself, and the qualitative and quantitative methods for acquiring movement data. The optimization of movement through ergonomic design of garments was discussed. Research employing various methods to study the effect of clothing on human movement was also reviewed. Most studies compared garments against each other with the aim of identifying the one which allows more mobility without seeking to identify the fabric/garment characteristics which made it so. A review of the literature about the doffing movement and clothing variables affecting doffing revealed that there is a paucity of research which addresses the effect specific garment and fabric variables have on doffing; with a few exceptions, most of the information is speculative in nature.

CHAPTER THREE

STATEMENT OF THE PROBLEM

I. THE PROBLEM STATEMENT

The purpose of this research is to develop and test a method for kinematic analysis of a particular garment doffing process. The specific objectives are to 1) identify the basic critical movements involved in the doffing process of a specific garment style, 2) quantify the movement pattern and 3) assess the validity of the method and reliability of the data.

II. CONCEPTUAL FRAMEWORK

This research is based on certain concepts from the design fields of human factors engineering and clothing and textiles. These concepts provide the rationale for the formulation of the objectives and hypothesis, and for the way the objectives were pursued.

The conceptual framework for analyzing the doffing process is based upon the concepts of functional fit of garments and functional anthropometry. Functional fit is that which spatially accommodates the two-dimensional garment pattern to the motion and activities of the body; functional anthropometric methods measure the human body in the dynamic posture assumed to perform a task. Both functional fit and functional anthropometry address the fit of the environment to human motion so that performance of a work task can be optimized in terms of efficiency, comfort, and safety. If garments are designed to functionally fit a clothing task, such as doffing, enabling the wearer to doff the garment without impediment to his mobility, higher levels of comfort and efficiency will result.

Both functional fit and functional anthropometry utilize measurements of joint motion that the body and its parts undergo when performing the desired task. The way in

which these measurements are obtained is supported by constructs and prinicples in biomechanics and physics. The range of motion of the body or its parts is a function of mobility, that is, the physiological capability of the joint to allow a movement. The range of motion can be obtained by modelling the body as a series of line segments (links) and joints as single points in space. The points in space representing joint centers can be obtained through application of photogrammetric theory which enables geometric reconstruction of an object from two or more different perspective projections. The perspective projections can be transformed into a three-dimensional object by a data reduction technique called **direct linear transformation** (DLT). This method yields the location of a point with coordinates from a set of two-dimensional image coordinates according to the following equations:

$$(b_1X+b_2Y+b_3z+b_4)-x(b_9X+b_{10}Y+b_{11}Z+1)=0$$
$$(b_5X+b_6Y+b_7Z+b_8)-y(b_9X+b_{10}Y+b_{11}Z+1)=0$$

where (X,Y,Z) are the object's calculated coordinates; (x,y) are the measured image coordinates, and the b_i's are the 11 DLT parameters to be determined. The segments between specified points in space represent the body (or portion of it). In classical mechanics, a segment behaves like the radius of a circle. As the body changes position, it rotates the radius along the circumference of the circle. The portion of 360 degrees circumscribed by the radius gives the angular displacement.

III. RESEARCH HYPOTHESES

The research hypothesis of this research are:

i. that the doffing process is comprised of basic critical movements that can be observed;

ii. that WATSMART is a feasible means for quantifying the movement pattern of doffing;

iii. that the method for quantifying the movement pattern is valid, and that the data are reliable.

IV. ASSUMPTIONS

The assumptions that were made in order to proceed with the research are as follows:

i. that the hardware of the measurement system (especially that attached to the subject) would not significantly alter the doffing process;

ii. that WATSMART is an accurate and reliable means of collecting data;

iii. that operator error with WATSMART system would be sufficiently small as not to affect the accuracy of measurement;

iv. that use of self as subject would not bias the collection of data;

v. that the wearing of undergarments would not significantly alter the doffing process or the collection of data.

V. LIMITATIONS

The methods and the results of this research are subject to the following limitations:

i. the method is not necessarily generalizable to any garment beyond those used in testing;

ii. the doffing movement of the subject cannot be assumed to be representative of the doffing movements of the population of women doffing such garments;

iii. the subject cannot be assumed to be representative of the population of women;

iv. the garments to be tested on the system are limited to those which are compatible with the WATSMART system;

v. the active-type markers of the WATSMART system may affect the doffing movement to some extent.

CHAPTER FOUR

DESIGN OF THE RESEARCH

I. BRIEF SYNOPSIS OF METHOD

An initial procedure for kinematic analysis of the doffing process was developed through pilot testing. **Doffing** refers to that set of basic, critical gross motions necessary for a wearer to remove the garment from her body (removing hair from face, movements of feet, fine motor movements of the fingers, eyelids, facial expressions and other incidental movements are not included). The movements of doffing were performed by a subject wearing a specific garment style made of a sheer fabric. The movements were simultaneously timed, filmed by video cameras, and recorded by an electro-optical motion analysis system (WATSMART). To identify the doffing movements, nominal analysis of joint movement was performed using a video motion analyzer on filmed trials. The movement pattern was quantified by calculating the angular displacement of joints from data collected by WATSMART which tracks the trajectory of infrared diodes attached to joint "centers". The angular displacement of joints was also estimated from video data using the Posture Taxonomy (PT) method. WATSMART data were compared for agreement with the PT ranges of motion to assess the validity of using WATSMART to study the doffing movement.

II. CRITERIA FOR ACCEPTABILITY OF A KINEMATIC ANALYSIS METHOD

The kinematic analysis method must be able, first and foremost, to analyze the movements of the limbs underneath a garment. It must be able to provide a quantitative measure of the range of motion. It must be able to describe the movement in precise qualitative terms so that it may be recreated on the strength of this description alone. It must be adaptable to many types of movements.

III. REASONS FOR SELECTION OF WATSMART SYSTEM

A major difficulty in measuring the range of motion in doffing is that the motion of the limbs cannot be observed because the opacity of the fabric obscures the body. One way to identify the motion of the limbs underneath clothing is to clothe the wearer in a garment made of sheer fabric. Sheer garments, coupled with a system that would allow identification of body segments and joint centers underneath sheer fabric and one that could analyze dynamic movements, not just static postures, could eliminate these difficulties. A photogrammetric system appeared to be the best choice to satisfy these requirements. WATSMART, one such system, was chosen because 1) IREDS are able to transmit through sheer fabric, 2) IREDS are relatively small and not likely to interfere with the movement, 3) WATSMART can preserve and recreate the motion in animated stick figure form, 4) data reduction is relatively simple since the system is computerized, and 5) the system is available in the Ergonomics Laboratory at Virginia Tech. Two potential sources of error in using WATSMART are that the system is prone to error from infrared reflection and that the IREDs are of the active type, the wiring of which can interfere with the normal performance of the movement.

III-1. DESCRIPTION OF WATSMART SYSTEM

WATSMART is an electro-optical system which automatically digitizes motions. It operates by tracking IREDS attached to the subject as the subject moves in a precalibrated space. Each camera produces two-dimensional coordinates from which three-dimensional coordinates can be calculated via direct linear transformation. WATSMART also has a useful feature which produces a visual record of the movement recorded: the subject is represented as an animated stick figure comprised of the line segments between markers. Under normal circumstances, this feature eliminates the necessity for using another system to provide a visual record.

III-2. OPERATION OF A WATSMART CAMERA

The transducer inside each WATSMART camera is a lateral-effect photodiode. The IRED on the subject emits infrared energy of 900nm which impacts on the photodetector, a 13mm silicon chip. This energy excites electrons into a higher energy state. The electrons then flow (creating a current), generating a voltage offset on the x and y edges of the diode. The distance from the point of light on the photodetector is directly proportional to the voltage offset. The ratio of the currents from opposite sides of the photodetector yields the two-dimensional location of the point of light. The system produces the most accurate data when at least two of the cameras are able to see the same point of light at the same time, thus yielding at least two estimates of (x,y) locations for the same point.

The (x,y) image coordinates are transformed into (X,Y,Z) object coordinates via direct linear transformation (DLT). There is a linear relationship between the image coordinates and the actual object location in the precalibrated space; DLT finds a "best fit" line to match this relationship. The more (x,y) estimates there are of a point, the better the accuracy of the calculation of the coordinates.

III-3. WATSMART SETUP PARAMETERS

The volume necessary to perform the doffing movement was observed. The volume calibrated was approximately a 3x1x1m space. Since WATSMART uses IREDS as the signal source, low IR reflectance in the measurement volume is crucial to the accuracy of the WATSMART system as accuracy varies inversely to the amount of IR reflectance (Kehl, 1986). Optimal performance was achieved under fluorescent lighting since both sunlight and incandescent light contain some infrared light which would confound signal reception by WATSMART cameras. Surfaces and objects in the viewing field of the cameras might serve as sources of infrared reflectance; these included the unitard undergarment on the subject and the floor of the testing area. The undergarment fabric

was tested by Northern Digital, Inc. for its infrared reflectance to assure its acceptability by the system. To measure the power of the reflected infrared light, a WATSMART camera records the light level from an IRED aimed at the test sample. All readings are normalized to a black metal reference surface. On the basis of the results, Northern Digital recommended turning the dull side of the unitard toward the cameras, which meant wearing the unitard inside out. Black Colortron foam, which has been found to have the least IR reflectance of any fabrics (Northern Digital, 1989), was used to cover the floor of the data collection field (approximately 18' x 18') to absorb any reflections. Surfaces and objects in the immediate viewing field that could not be removed were covered with foam as well. Cameras were positioned so that they pointed toward open space, rather than towards walls, possible sources of IR reflectance. As Northern Digital (1989) recommended, the cameras were placed no more than 60 degrees from one another and approximately equidistant from each other and from the calibrated space.

III-4. ACCURACY OF WATSMART

Kehl (1986) reported on performance measures of WATSMART. His findings are summarized as follows:

> "Accuracy, the agreement between actual positions and camera readings, was found to be within 1cm of actual location, and a standard deviation of 1.5 to 4mm for reconstructed 3D points." (p.2)

This accuracy is comparable to that found in other systems.

IV. DEVELOPMENT OF A VALIDATION METHOD

WATSMART is a digitally based data acquisition/reduction system, and has been validated by Northern Digital, Inc. (1986). The proposed method in the present research, however, used WATSMART in ways that this validation does not take into account. This was the first time WATSMART was being used to measure the range of motion of the doffing process, and the first time WATSMART was used with fabric covering the IREDs. This new, modified use of WATSMART required validation as well. Identifying a method was not a straightforward task since WATSMART is by far both more precise and

accurate than most other conventional analysis methods available today. Thus, an analysis with a conventional method, such as goniometry, would not reveal much about the validity of the WATSMART system. Since the desired output of WATSMART data was a quantitative record of the doffing motion, a method, or combination of methods, was needed that would also yield a quantitative record of the doffing motion.

IV-1. SELECTION OF A VISUAL RECORDING SYSTEM

It would probably have been best to use another three-dimensional system to assess the validity of the proposed modification of WATSMART, but such a system was not available at the time of this research. Two-dimensional analysis in the form of video filming was therefore employed to assess the validity of the method. Two-dimensional position vs. time data were obtained from video films by charting postures from different planar camera views, and establishing the time of occurrence for these postures. Since a two-dimensional method was used, it must be stressed that only a crude determination can be made as to the validity of the proposed method, i.e., it can only be stated whether the data obtained from the WATSMART system under clothed conditions agrees or disagrees with the two-dimensional data.

Video filming was chosen to provide a visual record because it does not interfere with the performance of a motion, and because it can be viewed repeatedly and in still form so that the range of motion can be measured. As Miller and Petak (1973) pointed out, the subject is spared much fatigue from sustaining a posture or from repeating it too often.

While the quality of cine filming exceeds that of video (faster filming speed, less grainy image), video filming was chosen over cine filming for three reasons. First, the use of the available cine camera (LOCAM) was prohibitively expensive. Second, only one LOCAM camera was available, and thus the inability to film multiple views would likely have contaminated the analysis. Third, had there been several cameras available and expense not a concern, the expertise to operate the camera (not to mention physical

strength as each camera weighs approximately 50 pounds) would require a trained technician to handle each camera, a cumbersome proposition. Preliminary filming of a subject doffing a jacket was done using a video camera and was found to be relatively easy and inexpensive, and to give a satisfactorily clear image both in still image and in moving image.

Four orthogonally positioned video cameras were used to record the doffing trials. Film speed was 60 frames per second for each. A Panasonic ProLine motion analyzer (Model AG-1960) was used to perform segmental analysis. Basically, this is a highly specialized video cassette player which projects a sustained image frame-by-frame.

IV-2. SELECTION OF A MOVEMENT NOTATION SYSTEM

In the Review of Literature, several ways of measuring joint motion were reviewed. Model simulation (Watson, 1984) could be employed, but for a dynamic motion, this method would be extremely time consuming and tedious for both measurer and subject. Alternatively, video film could be displayed frame-by-frame, and a goniometer used to take angular readings, but this would also be very time consuming. Malone's (1991) posture notation system was adopted because of its ease and speed of recording.

IV-2.1. Description of the Posture Taxonomy Method

The Posture Taxonomy method combines realistic depictions of the human form with a 360-degree target. A representation of the limb of interest is pictured in its own target, and also positioned at 15-degree intervals inside the target. The observer merely marks the limb in the target to most closely approximate the angle of the limb in space observed on the video film (Figure 5a, b, c). The instructions for using the PT method are provided in Appendix B.

The selection of Malone's (1991) Posture Taxonomy notation was based on several criteria: compatibility with frame-by-frame segmental analysis, speed of recording, accuracy of approximation of angular range of motion, and ease of use. Furthermore, PT

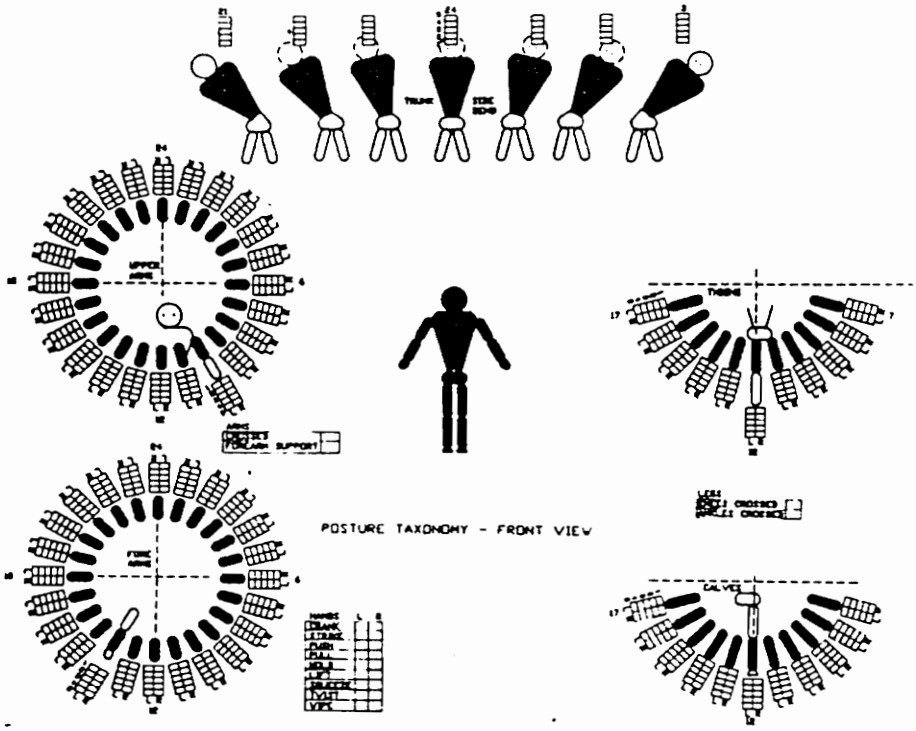

Figure 5
Posture Taxonomy
(a) Front View
Reprinted with permission from Posture Taxonomy
by Robert Malone, 1991

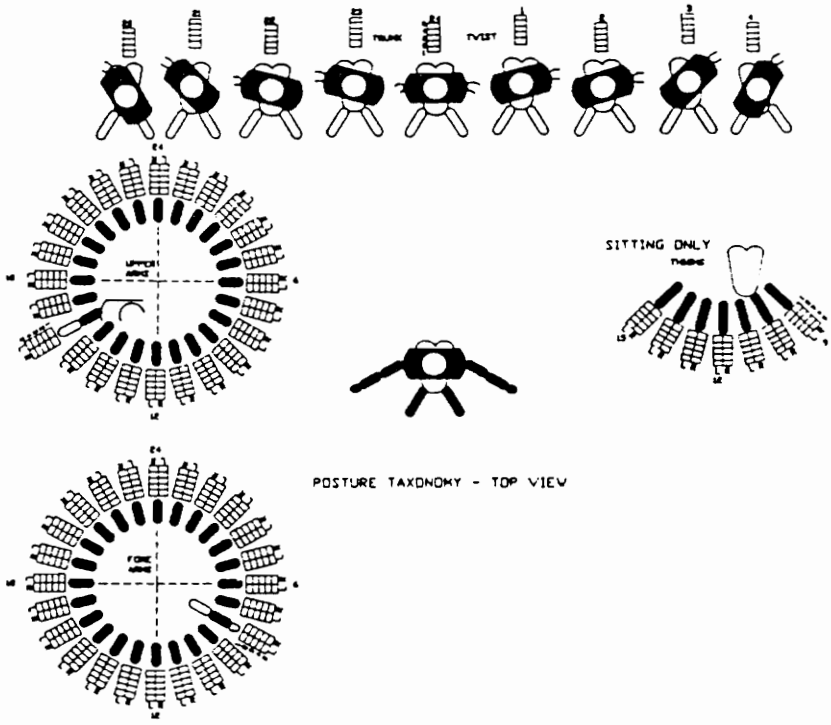

Figure 5 (cont'd)
Posture Taxonomy
(b) Top View

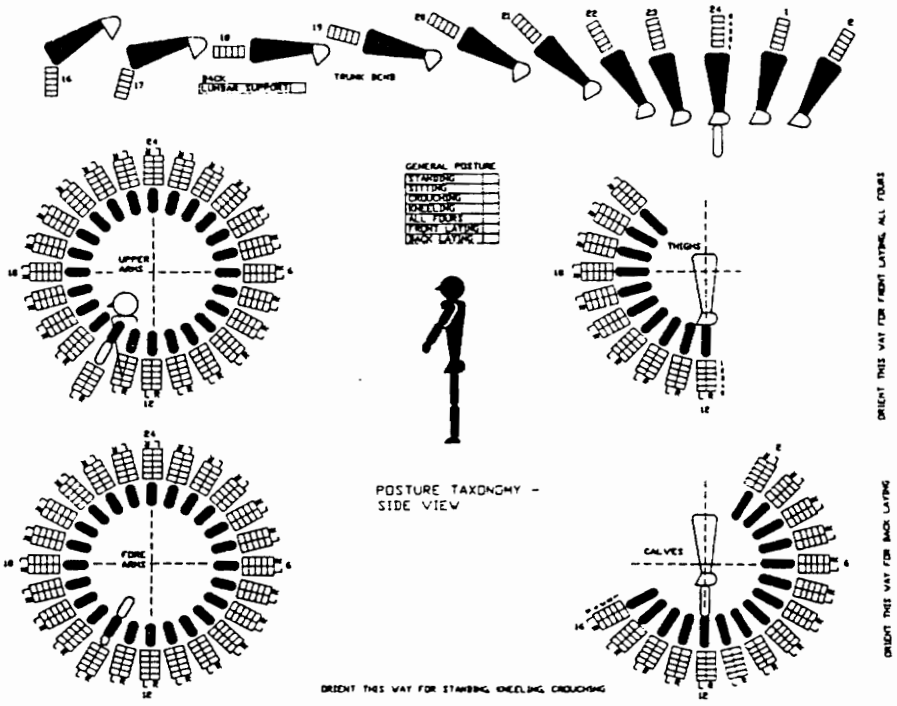

Figure 5 (cont'd)
Posture Taxonomy
(c) Side View

notation appeared to satisfy several of Guest's (1984) criteria (comprehensiveness, anatomical accuracy, logicality, visuality, legibility, and practicability). Malone's instrument was much more easily learned and used than any of the others reviewed. Posture recording systems such as those proposed by Birdwhistell (1970) and Kember (1976) required more effort to learn and translate because they use arbitrary symbols and are not as well known in the field. The posture targeting system developed by Corlett et al. (1979) was not as visually intuitive as Malone's, and the target as designed violated the principle of conceptual compatibility which may result in errors of substitution. Corlett et al.'s use of concentric circles to represent angular differences from the vertical axis might confuse those who are accustomed to measuring angular deviation in terms of radial lines. Priel's (1974) system required the ability to make absolute judgments about the angular displacement of a limb, which is harder for human beings than are comparative judgments (Malone, 1991). Most importantly, Malone's instrument had been validated.

One drawback of using the Posture Taxonomy instrument was that it was designed to record a static posture rather than a dynamic movement. Dance notation systems are more appropriate for charting dynamic movements, but the learning time is prohibitively long. While charting the movement frame-by-frame was possible, the amount of paper necessary would be quite cumbersome considering that there were 20 trials with an average of 295 frames in each and four views per trial. It was therefore decided to sample the doffing movement for key postures and chart only those.

Another factor that had to be considered was that Malone reported only moderate reliability in his validation. He attributed this result to operator error in approximating angles from the overhead view and to reversing left and right. Recorders were expected to imagine what the angular displacement would look like from the overhead view without actually seeing this view with their own eyes. Malone pointed out, however, that only two views are necessary to accurately plot the position of a three-dimensional object. It

TABLE 3
Roebuck's Terminology
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Table 3a
Roebuck's Terms to Describe Body Motions

New Term	Meaning	Replacing
-vection	pivoting of a body segment about its proximal joint, in two orthogonal axes	-duction
-torsion	twisting rotation of a body segment about its internal long axis	-nation
-rotation	rotation of a body segment about its major axis	rotation
(counter) clockwise	positive/negative rotation	supi-/pro-
-e-	away from zero (up, out)	ab-
-in-	towards zero (in, down)	ad-
Front-, Trans- Sag-	reference plane in which motion is described	none specified

Table 3b
Construction of Roebuck's Movement Terms
(Plane + Direction + Type = Motion)

Plane	Direction	Type	Example of Motion
Front(al)	-e-	-vection	frontevection
Sag(ittal)	-in-	-rotation	saginrotation
Trans(versal)	-e-	-torsion	transetorsion
(General case for any plane)	posi-	-vection	posivection
	negi-	-vection	negivection

was decided, therefore, to plot only those views taking place in the frontal and sagittal planes since the transverse plane was not filmed.

V. USE OF ROEBUCK'S TERMINOLOGY

In order to accurately describe the movement taking place, a precise verbal description was needed. The nominal analysis system proposed by Roebuck (1968) was chosen because its terminology is more precise and logical compared to existing medical and kinesiological terminology. His terminology indicates the direction in which the movement takes place, and can be compared against the direction indicated by the WATSMART data to assess veracity. Roebuck's terminology is relatively intuitive and utilizes the link model used by most biomechanical researchers. Further, his system is widely recommended by both ergonomists and functional clothing designers.

V-1. DESCRIPTION OF ROEBUCK'S TERMINOLOGY

The purpose of movement terminology is to provide a consistent description of body movements with respect to cardinal planes and axes. Roebuck selected a new root word "vection" (from Latin: *vehere, vectum*, "to carry") to connote the common engineering term "vector", since his system is based on changing the direction of vectors which represent the limbs of the body. The vector representing a limb of the body was termed the "principal director" and the vector perpendicular to the limb the "rotary director" (Figure 6). Specialized root words, "rotation" and "torsion", were selected to replace the medical terms supination and pronation. New prefixes were selected to indicate the spatial orientation of the vector and secondary prefixes to indicate direction of the vector. There are separate sets of terms for single links (only one link moves about a pivot point, e.g., the head and torso) and for dual links (two links move about a pivot point). Table 3a presents Roebuck's terms formed by various combinations of components and the traditional terms they replace; Table 3b illustrates the various components of his terms; Appendix C provides a glossary of the terms.

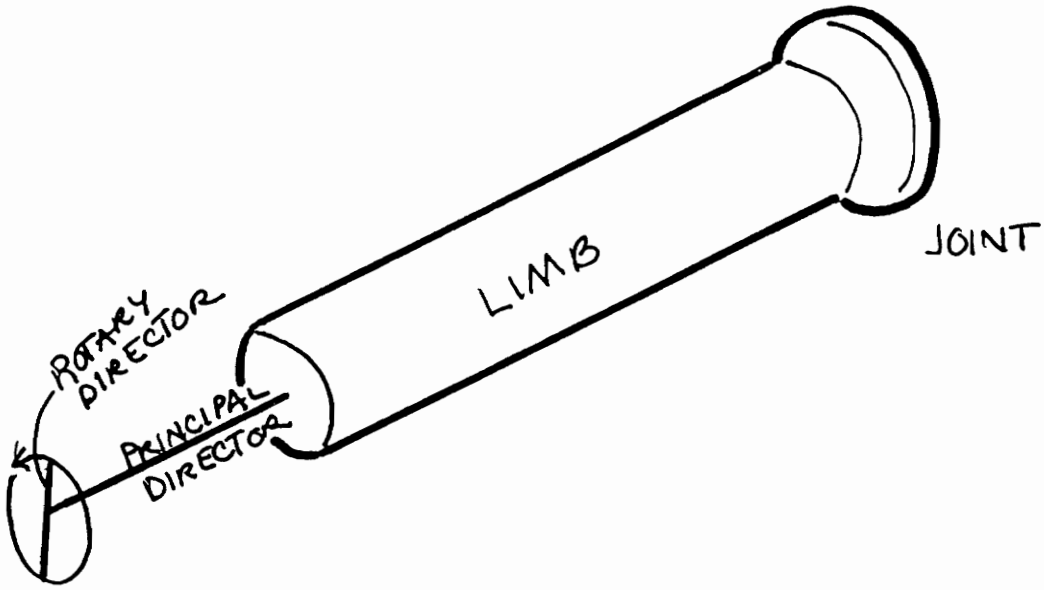

Figure 6

Model of Roebuck's Link Terminology
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VI. SELECTION OF SUBJECT

This research sought to develop a method for obtaining data rather than to generate definitive data. The choice of subject was based largely on convenience since the validity of the method had not been established at the time of data collection. It was decided therefore to use the researcher as subject. In fact, the validation of the method was expedited by use of a single subject. Using a single subject guaranteed that the qualitative and quantitative data collected would be free from inter-subject variability. Reduction of variability in the doffing movement was essential to identifying basic critical movements in WATSMART data collection as well as in validation.

The subject was a righthanded, 27 year old female in good health. The subject stood 5'2" tall and weighed approximately 108 pounds. The size garment usually worn by the subject was a misses 4/6 or XS. The subject had full use of all her limbs and could be characterized as possessing a high degree of mobility though within normal ranges.

VII. DEVELOPMENT OF A KINEMATIC ANALYSIS METHOD

VII-1. PRELIMINARY CONSIDERATIONS

The accuracy of WATSMART relied not only on the goodness of IR emission, but also on the goodness of the calibration. Calibration of the WATSMART system established a zero point for calculation of the coordinates. Calibration involved recording the position of an orthogonal frame (representing the cardinal axes) which has 40 built-in IREDs whose "true" locations are programmed into the computer. The WATSMART cameras recorded, then calculated the frame's IRED positions in space, and statistically compared the calculated positions of the IREDs with their "true" positions. It was found through trial and error that error was minimized by positioning cameras so that all three cameras (rather than only two) could see as many as possible of the IREDS at the same time. This required spacing the cameras further out from the calibration volume, thus increasing gain (indicating that the IR emissions received were less intense) but also providing three estimates of a reference point rather than two. IREDs with high gain

were suppressed, as were IREDs with high Euclidean error values (those whose calculated positions were far away from the "true" reference positions of the calibration frame). The calibration frame was repositioned so that the volume necessary to contain the movement could be calibrated. Frame positions with high (greater than 4mm) overall error were rejected. Two positions were found to possess a low enough overall error to calibrate the test volume. A multiple calibration was performed using these positions, resulting in an overall three-dimensional error of 2.51 mm.

VII-2. ENSURING VISIBILITY OF IREDs AND SUBJECT

It was necessary to determine the best location on the subject of the IREDs so that as many as possible could be seen by all three WATSMART cameras. High voltage IREDs ("triple markers") were used to reduce noise and increase the chances of transmission through the fabric barrier of the garment worn by the subject. Sixteen IREDs were affixed to the bony prominences of the upper body initially and the doffing movement was recorded. It was discovered that the IREDs on the elbow and shoulder were frequently lost to view. It was decided to increase the number of IREDs at these joints, but because of the limited number of available high voltage IREDs, the midbody IRED was removed. The new configuration of IREDs appeared to be the best possible for visibility (Figures 7). Table 4 lists the marker numbers, and the names of the corresponding bony landmarks. The line segments created by this final configurations of markers are shown in Figure 8.

It was necessary to determine a spot where the subject should stand to be in the field of view of all WATSMART and video cameras. Small monitors linked to video cameras were positioned on the periphery of the test area so that they could be seen by the subject, who stood approximately in the center of the test area. Using the monitor output as a guide, the subject positioned herself so that her image was orthogonally centered in each camera's viewing field. The equipment operator viewed the WATSMART stick figure output simultaneously on the computer monitor to select a position for the subject

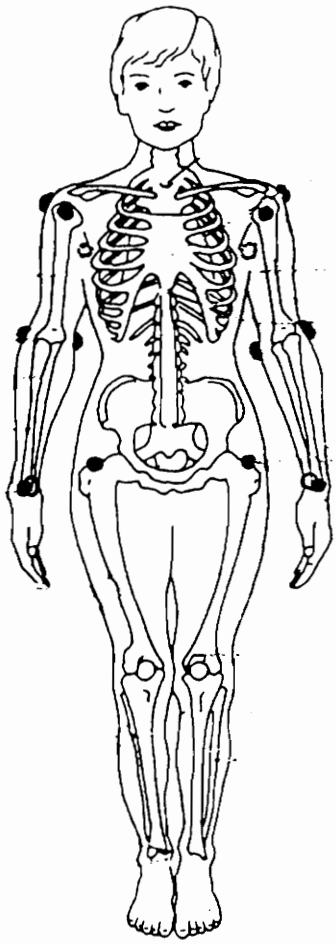


Figure 7

Final Configuration of IREDs
Figure Reprinted from Anthropometric Source Book
NASA Reference Publication 1024, 1978

TABLE 4

Placement of IREDs on the Subject's Body

IRED Number	Bony Landmark
1	Left ulnar stylion
2	Left radial stylion
3	Lateral epicondyle of the left humerus
4	Medial epicondyle of the left humerus
5	Lesser tubercle of the left humerus
6	Left armpit, approximate center
7	Greater tubercle of the left humerus
8	Anterior aspect of the left trochanteron
9	Right tubercle of the right humerus
10	Lesser tubercle of the right humerus
11	Right armpit, approximate center
12	Lateral epicondyle of the right humerus
13	Medial epicondyle of the right humerus
14	Right ulnar stylion
15	Right radial stylion
16	Anterior aspect of the left trochanteron

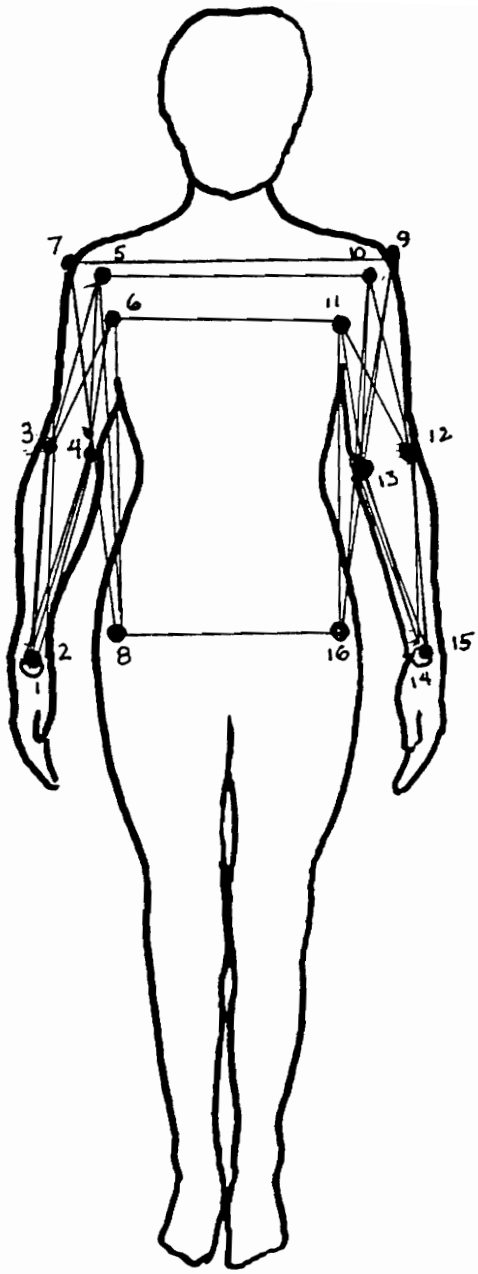


Figure 8
Link Segments Connecting IREDs

visible to both sets of cameras. This spot was marked by placing pieces of black electrical tape at the toes and heels on the Colortron foam covering the floor.

VII-3. GARMENT AND FABRIC SELECTION

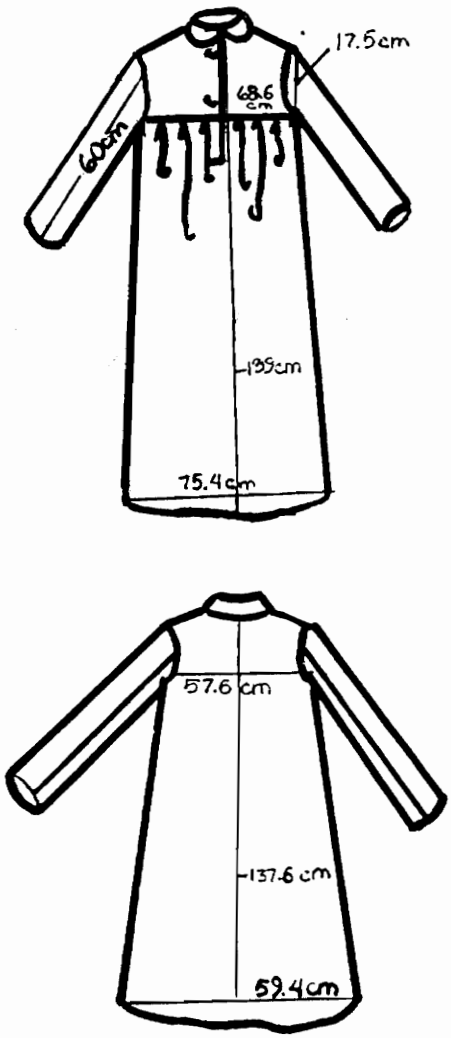
The garment style to be tested was selected on the basis of three criteria: 1) design features that affect garment doffing based on dimensions and configuration; 2) frequency of use of the style; and 3) compatibility with the WATSMART system. For the purposes of this research, women's nightgowns were selected because they a) are frequently worn by many women and b) certain styles possess design features that make doffing difficult for the wearer. Nightgowns are garments particularly well-suited to methodological development with the WATSMART system because they are commonly made from sheer fabrics (the importance of this will be described below) and because they are essentially cylindrical in shape, which allows easy maneuverability over the cable which leads from the system to the subject. Research has shown that design impediments to doffing nightgowns include long sleeves, cuffs and elasticized wrists, high necklines, fitted waists and bodices, floor length skirts, and such fasteners as ties, small buttons, placket lacings, and back closures (Caddel, 1977-78 cited in Norton, 1980; Johnson, 1976; Norton, 1980).

For this study, two nightgown styles were purchased from national department stores under the assumption that these stores would carry current, popular styles which would be representative of the styles worn by most women. Two styles were chosen: one that possessed several impediments to doffing, and one that did not. The former is referred to as **Purchased Garment S** (for Short) and the latter as **Purchased Garment L** (for Long) and are characterized in Figure 9. Their test counterparts made in sheer fabrics are referred to similarly: Test Garment S and Test Garment L. Films made by Norton (1980) of doffings of many nightgown styles were viewed to aid in the selection of these garments.

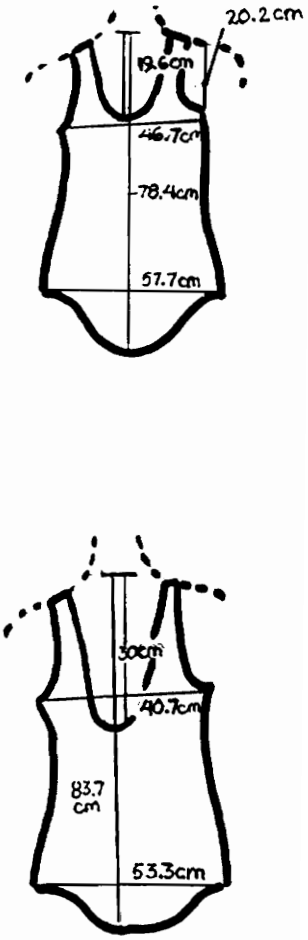
Figure 9

CHARACTERIZATION OF GARMENT

Purchased Garment L



Purchased Garment S



	Purchased Garment L	Purchased Garment S
Source	Sears, Roebuck & Co.	Sears, Roebuck, & Co.
Style Number	7313	13181-081
Style Description	Long, slim silhouette; 2-piece fitted set-in sleeves; shirttail hem; no cuffs, high neck with 2 buttons in front placket in yoked bodice; Peter Pan collar	Short, loose tank; bias cut; no fasteners

VII-3.1 Construction of the Test Garments

The purchased garments were unsuitable for use with the WATSMART system because of their opaqueness; duplication in a sheer fabric was necessary. The purchased garments were separated into pieces, traced onto paper to form patterns, and transferred to nylon tulle. The test garments were sewn in nylon tulle, using lapped seams overlaid with lace tape and stitched with a zigzag stitch. While the original garments had 3/8" serged seams, the open nature of tulle required a different seaming technique to provide stability. Neck edges, sleeve openings, and hems were stay-stitched rather than faced or hemmed to preserve the sheerness as much as possible. The collar of Test Garment L was omitted also for this reason. The degree of simulation, i.e., the extent to which the visual appearance of the test garments emulated the actual garments, was considered satisfactory since the original garment shape was retained. The degree of fidelity, the extent to which the behavior of the test garments emulated the purchased garments, was compromised somewhat by the difference in fabric properties of the tulle fabric, but was assumed for the time being to be satisfactory since the original joinings and dimensions were retained.

VII-3.2 Selection of Test Fabric

The fabric comprising the test garments needed to be sufficiently sheer to allow the motion of the body within the garment to be seen on the video film and to allow the IREDs attached to the body surface to be recorded by the WATSMART system. The WATSMART system was able to receive IRED emissions only if the fabric was open enough to allow penetration of the signal.

Cheesecloth was pretested on the WATSMART system by draping the fabric over a broom (IREDS attached) and collecting data in five different angular positions. The data were converted to three-dimensional coordinates and viewed in graphic format. Very little "noise" was exhibited by the stick figure images, that is, the line segments did not appear to be distorted or quivering. Since the preliminary results were encouraging, a doffing trial was run with a nightgown-type garment constructed in cheesecloth. Ten

IREDS were attached to the subject with the wires taped down to the arms. The excess wire was contained by the unitard worn by the subject under the test garment. The data were collected, converted, and viewed as before, and again little distortion of the stick figure was observed. It was decided that the use of a sheer fabric in the test garments was a feasible solution.

The imposition of any fabric between the cameras and the IREDs, no matter how sheer the fabric, will introduce some noise into the data. Infrared radiation can be emitted, transmitted, reflected, or absorbed; emission without interference would maximize the accuracy of the signal. It could be hypothesized that a fabric which possesses large interstices would probably introduce less noise. This property is referred to as cover factor (CF), which obeys the relationship:

$$CF = \text{Fabric Count} \times \text{Denier}^{1/2}$$

Several test fabrics of low fabric count and of varying fiber content were obtained to select one that would induce the least amount of noise in the data. Cover factor, however, only characterizes woven and knit fabrics. This is a problem because some of the test fabrics under consideration were neither woven nor knit. Furthermore, cover factor gives no quantitative measure of the noise induced in data collection. Therefore, the use of cover factor alone was not adequate for selection of the fabric. The calibration frame and the calibration software of the WATSMART system could have been used to estimate the error induced by a given fabric. As discussed above, this software, among other functions, computes the two-dimensional and three-dimensional errors in a calibration. The calibration method would involve recording the calibration frame by itself, then draping a fabric over the frame, recording the calibration frame again, and comparing the error associated with the naked calibration frame with that of the draped calibration frame. The problem with this method is that high voltage IREDs would be utilized in the actual data collection, but the calibration frame is equipped with only low voltage IREDs, which would not give an actual representation of the error suffered during data collection.

To estimate the error likely to be suffered under test conditions, it was decided to test the fabric by collecting data using high voltage IREDs. Two IREDs were attached to a stationary object and their positions recorded by the WATSMART system. These IREDs are referred to hereafter as the reference IREDs. A swatch of fabric was then draped over the IREDs and the positions recorded again. This procedure was repeated for each candidate fabric. The standard deviation and mean location of both IREDs were calculated by the MEAN program of the Data Analysis Package (provided with the WATSMART system). The results of this analysis are presented in Table 5. A polyester lace and a polyester/cotton voile were eliminated because of their high standard deviations compared to those of the other fabrics. For each of the two reference IREDs, the difference between the calculated location of the reference IRED and the observed location of the IRED draped with each successive fabric (black nylon tulle, black polyester point d'sprit, black polyester chiffon, and white cotton cheesecloth) were calculated according to the following equation:

$$[(x-x_o)^2 + (y-y_o)^2 + (z-z_o)^2]^{1/2}$$

where x_o, y_o, and z_o are the means of the observed locations of the draped IRED, and x,y, and z are the true coordinates of the reference IRED. ANOVA (Lintze, 1990) showed showed significant differences between the different fabrics (Table 6a). This fabric was identified by calculating the square root distance and standard deviation for the draped positions; nylon tulle had the lowest values for both and was chosen as the most appropriate fabric to use as the test fabric (Table 6b).

As described in the Review of Literature, fabric properties can affect the doffing process. The fabrics of the purchased nightgowns and the chosen test fabric were further characterized by fabric structure, cover factor, thickness, weight, flexural rigidity, fiber content, stretch, and immediate growth and growth after static extension to provide some insight into any differences encountered between doffings of the purchased garments and the test garments (Table 7). American Society for Testing Materials (ASTM) procedures

TABLE 5
Means and Standard Deviations Associated With Calculation of Reference IRED Location Due to Imposition of Fabric Barrier

No Fabric

IRED	Axis	N	Mean	SD
1	X	251	-286.9677	0.7313
1	Y	251	350.7434	0.7789
1	Z	251	407.8614	0.8999
2	X	251	-570.0466	0.9455
2	Y	251	233.7610	1.3836
2	Z	251	411.3649	1.2488

Nylon Tulle

IRED	Axis	N	Mean	SD
1	X	251	-286.1434	1.1467
1	Y	251	343.5920	1.4262
1	Z	251	406.4287	1.1314
2	X	251	-574.6255	0.9693
2	Y	251	239.4450	1.6258
2	Z	251	405.6131	1.4172

Polyester Point d'Sprit

IRED	Axis	N	Mean	SD
1	X	251	-291.7076	0.7169
1	Y	251	361.6920	0.9885
1	Z	251	401.5618	0.9111
2	X	251	-573.4896	1.4490
2	Y	251	226.8629	1.3364
2	Z	251	399.3685	1.4276

Polyester Chiffon

IRED	Axis	N	Mean	SD
1	X	251	-289.7335	0.6349
1	Y	251	361.0347	0.8702
1	Z	251	399.0367	1.1497
2	X	251	-571.8315	1.3990
2	Y	251	227.4398	1.4470
2	Z	251	395.3924	1.6265

TABLE 5 (cont'd)

Polyester Lace

IRED	Axis	N	Mean	SD
1	X	251	-286.9614	1.3223
1	Y	251	345.9625	1.6540
1	Z	251	418.9992	1.5236
2	X	251	-575.9319	1.2122
2	Y	251	242.1215	2.1014
2	Z	251	407.7853	1.7627

Polyester/Cotton Voile

IRED	Axis	N	Mean	SD
1	X	251	-287.3303	0.8908
1	Y	251	360.8534	1.2293
1	Z	251	394.9876	1.1334
2	X	251	-546.2052	9.1513
2	Y	251	230.2761	2.5411
2	Z	251	394.5757	4.0937

Cotton Cheesecloth

IRED	Axis	N	Mean	SD
1	X	251	-295.7478	0.9124
1	Y	251	356.8972	1.1153
1	Z	251	402.4239	1.2219
2	X	251	-571.4155	1.0017
2	Y	251	236.2749	2.0385
2	Z	251	400.4351	2.1719

TABLE 6
Fabric Selection Statistics

Table 6
Analysis of Variance on Square Root Distance Between Actual Location and Perceived Location of IREDs Underneath Various Fabrics

ANOVA Results					
	MS_b	SS_b	MS_w	SS_w	F-Ratio
IRED 1	2134	6403	.787	784	2712.6
IRED 2	2937	8812	2.36	2354	1242.8

Table 6b
Square Root Distance of Draped IRED to Reference IRED and Associated Standard Deviation

Fabrics	IRED 1		IRED 2	
	Sq. Root Distance	Std. Dev.	Sq. Root Distance	Std. Dev.
Nylon Netting	7.57	1.1	9.53	1.1
Poly Point D'Sprit	13.58	.69	14.4	1.2
Polyester Chiffon	13.91	.92	17.4	1.6
Cotton Cheesecloth	12.15	.82	11.6	2.1

(see Table 7) were used when applicable in fabric characterization. One exception was the procedure used for determination of cover factor for which no ASTM procedure exists. The determination of cover factor for nylon tulle was difficult because it required the denier of the yarn to be known. Determination of denier required a 1 meter length of yarn, which was impossible to unravel from the tiny raschel knit. The denier of the yarn of the tulle was therefore approximated to be at least as large as the yarn of the polyester satin, but smaller than that of cotton flannelette. Therefore, the cover factor reported for the netting is based on the denier of the polyester satin yarn multiplied by 1.5.

VIII. PROCEDURES FOR DATA COLLECTION AND ANALYSIS

The subject was filmed by video cameras, and simultaneously body motion data were collected by WATSMART (Figure 10). The subject was filmed from four orientations (sagittal right, sagittal left, anterior, and posterior) using four video camcorders at a filming speed of 60 frames per second.

First, the WATSMART and video cameras were positioned, and the test volume calibrated. The subject, wired with IREds and clothed in the test garment, stepped into the test volume in a position such that she was centered in the optical field of all seven cameras. A clapboard (held by an equipment operator) with the date, trial number, and location of the test was filmed by the frontally oriented camera and was then laid aside. The WATSMART system was activated by the equipment operator, who simultaneously signalled the subject verbally to begin doffing. The subject then doffed the garment and assumed the standard position at the completion of the doffing process. The subject performed the doffing movement in each test garment 10 times to eliminate extraneous movements from the doffing process, establishing a constant skill level. The process was repeated until 10 trials had been recorded for each Test Garment S and Test Garment L. The films were viewed repeatedly to gain familiarity with the doffing process.

TABLE 7
Characterization of Fabrics

Property	Fabric S	Fabric L	Test Fabric
Fiber Content	100% Cotton	100% Polyester	100% Nylon
Fabric Type	Plain weave flannelette	Satin weave, 2 over 1	Rashcel knit tulle
Fabric Count ASTM D3775 - 84	53.6 x 45.6 w/f	100 x 110.8 w/f	23 x 37 c/w
Yarn Number	42.2 cotton count	432 denier	648 denier (est)
Cover Factor	601.6	2078.5	585.5
Weight ASTM D3776 - 84	2.25 g/m	1.40 g/m	0.205 g/m
Thickness (precomp) ASTM D1777 - 64	.0309"	.0072"	.007"
Flexural Rigidity ASTM D1388 - 64	18.39	6.28	4.804
Stretch* ASTM D3107 - 75	87%	68%	269%
Immediate Growth* ASTM D3107 - 75	32.6%	30.7%	127.6%
Static Growth* ASTM D3107 - 75	3.88%	0.4%	ruptured

*test not performed in conditioned atmosphere

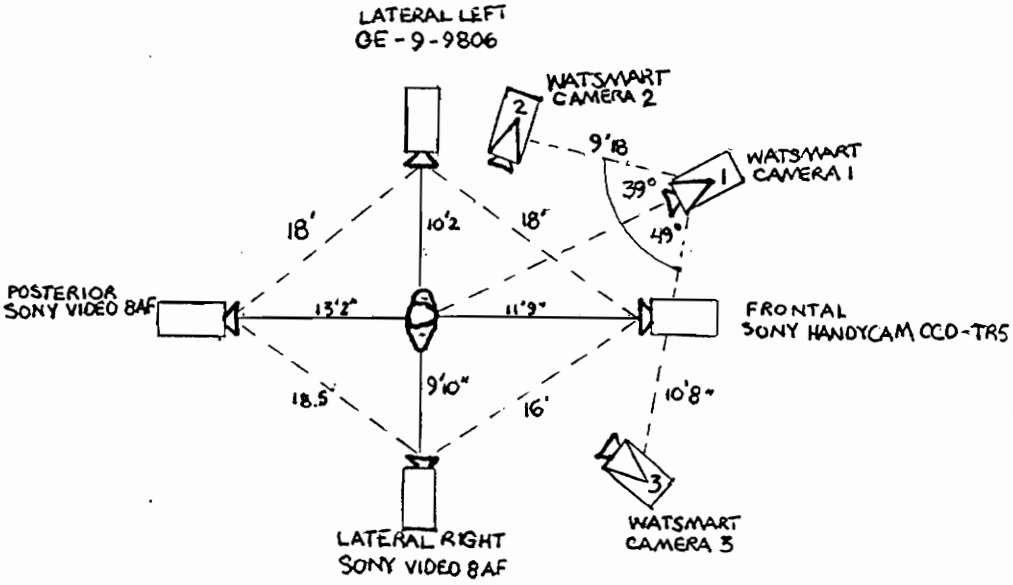


Figure 10

Experimental Setup of Data Collection

VII-1. IDENTIFYING CRITICAL MOVEMENTS OF THE DOFFING PROCESS

To identify critical movements in the doffing process, doffings in each style of nightgown were filmed by video cameras positioned as described in section VII-2. The video films were viewed in stop-frame sequence on a professional quality video player and segmental analysis performed as described by Northrip, Logan, and McKinney (1974). Movements were classified according to Roebuck's terminology for each critical movement using links to approximate limbs and joint centers as per the link model.

VII-1.2. Video Data Collection Procedures

The video films were viewed repeatedly to gain familiarity with the doffing process. From the repeated viewing of the video films of both the test and purchased garments, the same movements were found to occur regardless of the garment style being doffed. A sequence of basic, critical movements of the doffing process was identified by the investigator. These movements are those which directly accomplish removal of the garment. The movements were identified on the basis of two general criteria: a change in direction of the limb, or a change in the plane of occurrence were considered to constitute a basic movement. Twelve critical movements which were identified are illustrated in the Results and Discussion chapter and have been assigned Roman numerals. This sequence of 12 movements was used in several ways: to provide an abbreviated record of the doffing process, to characterize phases of the process, and to provide a pool from which samples of planar movements could be selected for later use in validation.

The four distinct phases of the doffing process appear to be: removal of the garment from the lower torso, removal of the garment from the upper torso, removal of the garment from the head, shoulders, and left arm, and finally, removal of the garment from the right arm. This same sequence of movements can also be identified in the films made by Norton (1980).

As pointed out earlier, the Posture Taxonomy method was designed to chart static postures, while the doffing movement is a dynamic process and so a frame-by-frame

analysis would result in an unwieldy amount of paper. Of the 12 critical identified movements of the doffing process, six postures were selected to be charted using the PT method. These postures are referred to as **temporal matching postures**, the postures which could establish a match in terms of angular displacement and time between the video record and the WATSMART record. Except for the start and finish positions, these postures were selected because they could be characterized as planar postures, that is, the angles formed by the body appeared to occur in one of the cardinal planes. It was hoped that the estimation of the angular displacement for these postures would not be as prone to error as those taken from nonplanar postures. The six temporal matching postures are described below, their numbers corresponding to their assigned Roman numerals in the total sequence of 12 critical movements illustrated in a later figure.

i) Reading taken at start position, elbows flexed, shoulders flexed, hands covering hip IREDs

ii) Reading taken when hands pinch bottom of garment; arms more extended than in position (i)

vi) From right and left sagittal views, reading taken at earliest point at which upper arm is approximately perpendicular to torso

vii) Reading taken at earliest point that arms are crossed overhead, elbows at approximately 90 degrees flexion, and elbow joints sharing same x-axis

viii) Reading taken at point when, respectively from right and left sagittal views, right/left arm is raised above head and head drops forward to meet chest

xii) End position; see (i)

In order to compare the events recorded by WATSMART and those recorded by video, common starting and ending points were needed. In video or cine filming, usually auditory and visual signals are employed in the form of a "clapboard". The WATSMART system, however, does not recognize audio signals or visible light wavelengths, but only

infrared wavelengths of light. It was decided, therefore, to reveal certain diodes at the beginning of the trial and obscure those same diodes at the end since the presence/absence of a diode's infrared signal would be recorded by WATSMART, while the covering and uncovering of the diodes would be detected by the video cameras as well. The PT instrument was designed to allow charting of five separate trials on one page, but sacrificed clarity. Thus, it was decided to chart just one trial per page. The range of motion was estimated in terms of relative angular displacement (that angle between two segments). The angular displacement of the limb was indicated by estimating its **absolute** position, that is , its displacement from the reference position (6'o'clock on the vertical axis). In the case of the elbow, simple geometry was employed to resolve the absolute positions of the forearm and upper arm into the **relative** angular displacement. Since the torso was largely immobile, the absolute angle between the upper arm segment and the torso defined the relative angle as well.

In addition, the times at which postures occurred in each trial were determined. This was done by counting the number of frames and converting the frames to seconds. The frames were counted three times and the average of these estimates calculated. The time in seconds at which these events occurred could then be obtained by the following relationship:

$$\frac{1 \text{ second}}{60 \text{ frames}} \times \text{no. of frames} = \text{no. of seconds}$$

The reliability of these measurements was assessed by computing the standard deviation for the three frame counts for each trial, shown in Appendix D.

VIII-2. QUANTIFYING THE MOVEMENT PATTERN USING WATSMART

The second objective, to quantify the boundaries of the movement pattern, was accomplished by a modifying the WATSMART system. This modification was imposing a fabric barrier between the IRED and the camera; the fabric barrier due to the sheer fabric of the test garment. Data collection yielded the three-dimensional location of each joint

center (approximated by IREDs) for each doffing trial over time, but what was wanted was the boundary of the movement pattern. The relative angle formed between the line segments connecting the IREDs was calculated. These angles should represent the movement pattern the limbs underwent in performing the doffing movement.

The volume of space to be used for the procedure was calibrated as described below. A total of 16 IREDS was attached to the subject (who was wearing a closefitting sleeveless unitard) at selected bony landmarks of the upper body as described above. The IREDS were attached to the subject by double-sided adhesive and the wires taped down to reduce interference with the doffing procedure; black electrical tape was used to reduce the possibility of IR reflection. Excess wire from the IREDs was tucked into the unitard. Initially, the subject was timed while doffing the garment to establish the amount of time each WATSMART camera should collect data. A collection time of seven seconds was set based upon this pilot-test doffing. The rate at which the WATSMART cameras sampled the movement was 200hz, or 200 frames per second. This high frequency rate ensured smooth data after processing. The subject began doffings of the test garment, each doffing being recorded by WATSMART cameras. Ten trials were recorded. All doffings were performed over the head to provide a consistent record of the doffing process.

Three data collection sessions were conducted over a period of four months. The first set of data was rejected because many of the IREDs were obscured during the movement. The second set of data was unusable because a file of parameters necessary to convert the raw data to three-dimensional coordinates was inadvertently erased. The third set of data was used in this research.

VII-2.1. Reduction of the WATMART Data

The raw data recorded initially by WATSMART were the two-dimensional coordinates of the voltage offset. These data were converted to coordinates via direct linear transformation without linear splining, the interpolation of blocks of missing two-dimensional data by calculating the straight line equation between two good data points).

The three-dimensional coordinates were filtered at 10hz using a Butterworth filter to eliminate high frequency noise, then converted to floating point format for compatibility with another software package, the Data Analysis Package (DAP) in WATSMART. From the points in space, relative angles of the left and right shoulders and elbows for each trial were calculated using the DAP software program provided with the WATSMART system. The relative angular positions were plotted against time using HALO (Media Cybernetics, 1986) software. These plots are based on numerical data sets of about 10,000 points. Figure 11 shows an example of a plot and interpretion.

Each dual-link is described by two or more configurations of IREDs which results in different estimates of the same angle. Figure 12 illustrates how the line segments between different markers on the same joint can result in different angular values. The data generated by each IRED were examined to determine how well the IRED could be seen. Those IREDs that could not be seen at least half the time were not included in the conversion to relative angles. For instance, IREDs 9 and 7 generated very sparse data, indicating that they were often not seen by the cameras. For all 20 trials, IREDs 9 and 7 were excluded from analysis. Excluding IREDs from analysis reduces the number of configurations, resulting in fewer values of the joint angle. For each trial, angles derived from the remaining configurations of IREDs were graphed vs. time to provide a picture of intra-trial consistency.

The intra-trial consistency graphs were examined to identify which configurations of IREDs most completely represented the doffing motion as recorded using the PT method. The traces from the most complete configuration of IREDs for each trial for each garment type were then superimposed on one another to provide a picture of the consistency of the doffing performance by the subject. The data for each plot were standardized for time using the first appearance of the hip IREDs as a starting point.

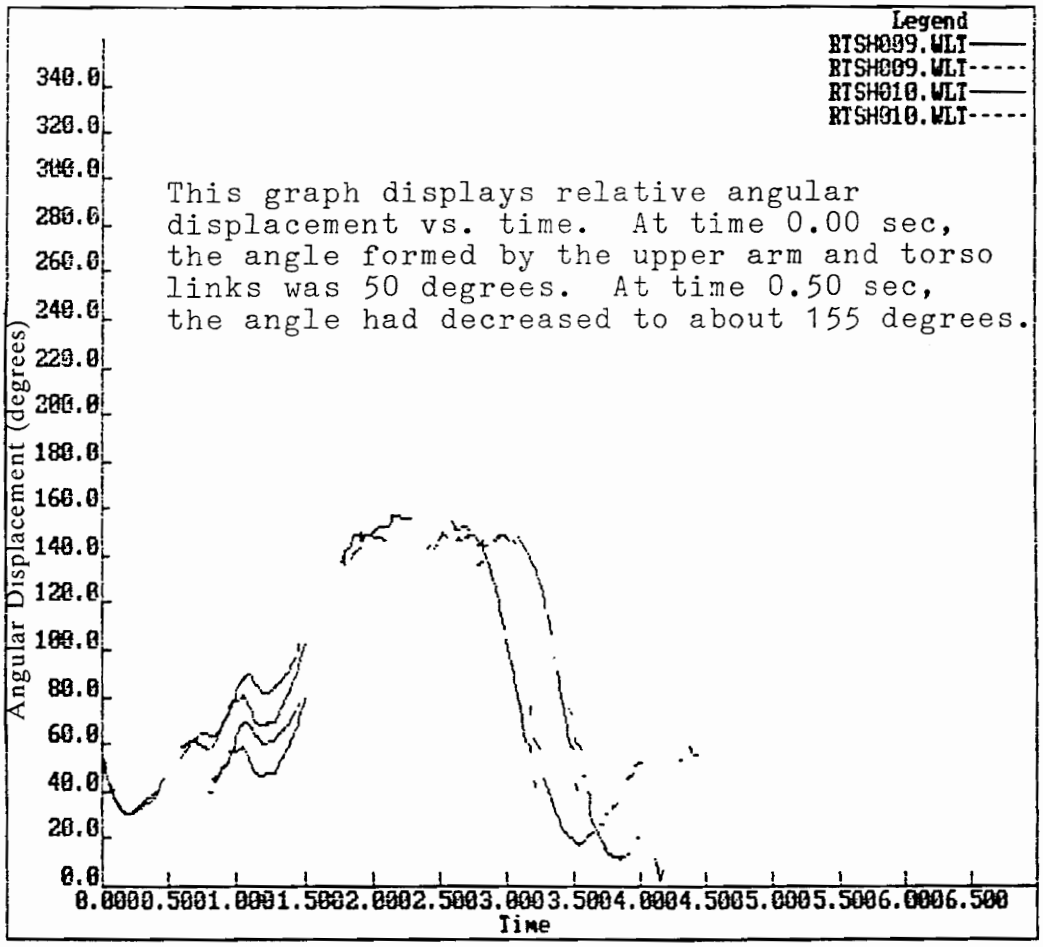


Figure 11
A Typical Graph of WATSMART
Position vs. Time Data

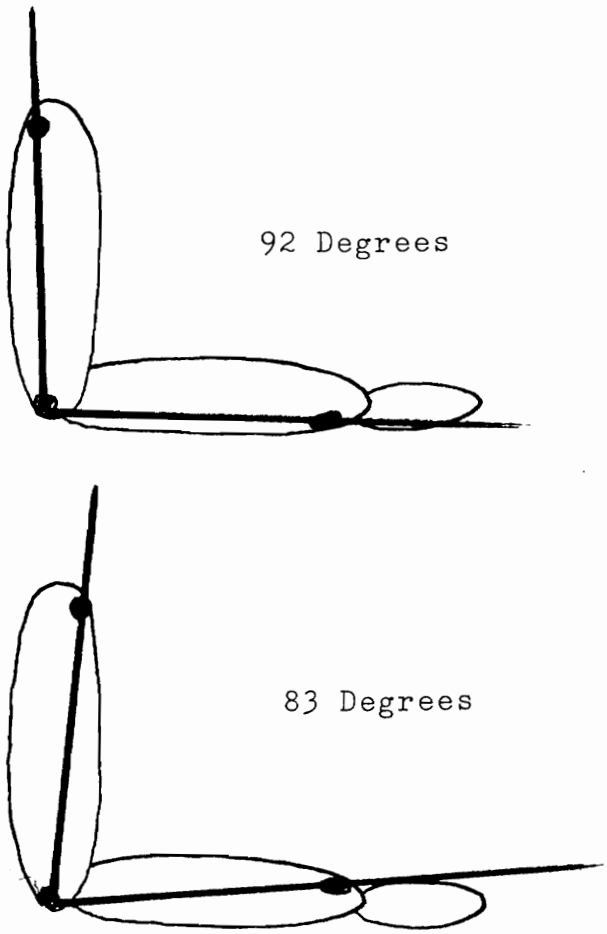


Figure 12
Two Configurations of IREDs for the Elbow Joint Resulting in Different Angular Values

Plots were made of each individual trial using the most complete configuration of IREDs. The video position/time data were again graphed overtop these graphs to establish whether the WATSMART data matched the video data temporally and positionally.

IX. PROCEDURE FOR ASSESSING THE VALIDITY OF THE METHOD AND RELIABILITY OF WATSMART DATA

IX-1. ASSESSING THE CONSTRUCT VALIDITY OF THE METHOD

Kerlinger (1973) defines three types of validation: content (face), criterion-related (predictive), and construct. The last attempts to validate the theory behind the test. It is this type of validation that was explored in this research to satisfy objective three.

One requirement of construct validation is evidence of convergence, that is, "...evidence from different sources gathered in different ways all indicates the same or similar meaning of the construct" (Kerlinger, 1973, p. 462). To operationalize this definition, the validity of the measurement of doffing motion can be affirmed if the data which describe the motion (time, range of motion, direction) obtained by WATSMART are the same or similar to data obtained by another method.

Constructs of validation include the degree of simulation and fidelity of the test garment to the purchased; the degree of simulation and fidelity of the movements in the test garment compared to those in the purchased; and the degree of agreement of the video data to the WATSMART data. The first two of these components were evaluated according to the following general criterion: if there were no evident differences between the movements performed with the test garments as measured by the type and sequence of movements and the movements performed with the purchased garments as shown by the video tape, then it was concluded that movements performed in the test garments were acceptably representative of those performed in the actual garments. Thus the data collected by WATSMART of the movements performed in the test garments could be judged as representative of the data that would result if the movements were performed in the purchased garments.

Since WATSMART is a three-dimensional system, comparison against another three-dimensional system of accepted accuracy and validity would be most desirable. However, no other system was available in the facilities in use. Comparison of the WATSMART system was therefore conducted against a two-dimensional system of accepted validity and accuracy. The WATSMART-derived position vs. time data and that estimated by the Posture Taxonomy method were compared. Further, the direction of movement as indicated by Roebuck's terms was compared to the position/time data derived from WATSMART. If the WATSMART position/time data matched the position/time data taken from the video films, and the directions of the movements were the same as those observed on the video film, then it was concluded that the data collected by WATSMART of the movements performed in the test garment could be judged as representative of the data that would result if the movements were performed in the purchased garment. This necessarily means that only a crude determination is made as to whether the WATSMART data agree with the two-dimensional data.

IX-2. ASSESSING RELIABILITY OF THE DATA

Reliability is comprised of accuracy and consistency. Assessing the accuracy of WATSMART range of motion data would presume the existence of a "true" set of range of motion figures for the doffing movement, data which do not exist. Therefore, accuracy of WATSMART data cannot be addressed to assess reliability. Assessing the consistency of WATSMART data can be accomplished by analyzing the degree of similarity of the data between trials (inter-trial consistency) and within trials (intra-trial consistency). Intra-trial consistency was analyzed by plotting different estimates of the same joint angle for each trial on the same graph. The degree of agreement of the different estimates shows the consistency of data collection within a trial. Inter-trial consistency was analyzed by plotting the same estimate of each joint angle for each trial on the same graph. The degree of agreement between angular displacements of different trials for the

same joint angle provides a measure of consistency of the subject's performance between trials.

CHAPTER FIVE

RESULTS AND DISCUSSION

I. INTRODUCTION

The objectives of this research were to: 1) identify the basic critical movements involved in the doffing process of a selected garment style, 2) quantify the movement pattern, and 3) assess the validity of the method and the reliability of the data. This chapter is divided into three sections which present the data corresponding to the above objectives. First, the results from video analysis for each garment type, from which the basic critical movements were identified, are described by general terms and Posture Taxonomy angular displacement estimates, and categorized by Roebuck's terminology. Next, the angular displacement data obtained by WATSMART, which quantified the movement pattern, are presented with accompanying figures plotting these data over time. Finally, the PT range of motion data and WATSMART range of motion data are compared on the basis of temporal matching postures to assess the construct validity of using WATSMART to study doffing. The degree of fidelity observed between the purchased garments and the test garments is discussed to further assess the validity of using WATSMART to study doffing. Reliability of WATSMART data is addressed as intra-trial consistency and inter-trial consistency. This discussion follows the discussion of validity.

II. CRITERIA FOR THE ADMISSIBILITY OF DATA

To be admitted for analysis, WATSMART and video results had to satisfy several criteria. The films had to be visually clear, and complete in terms of time. WATSMART records had to be complete and exhibit low noise. The movements recorded by both systems had to be representative of the doffing movement in general. Interruptions in the doffing process due to external causes and hardware problems could alter the doffing

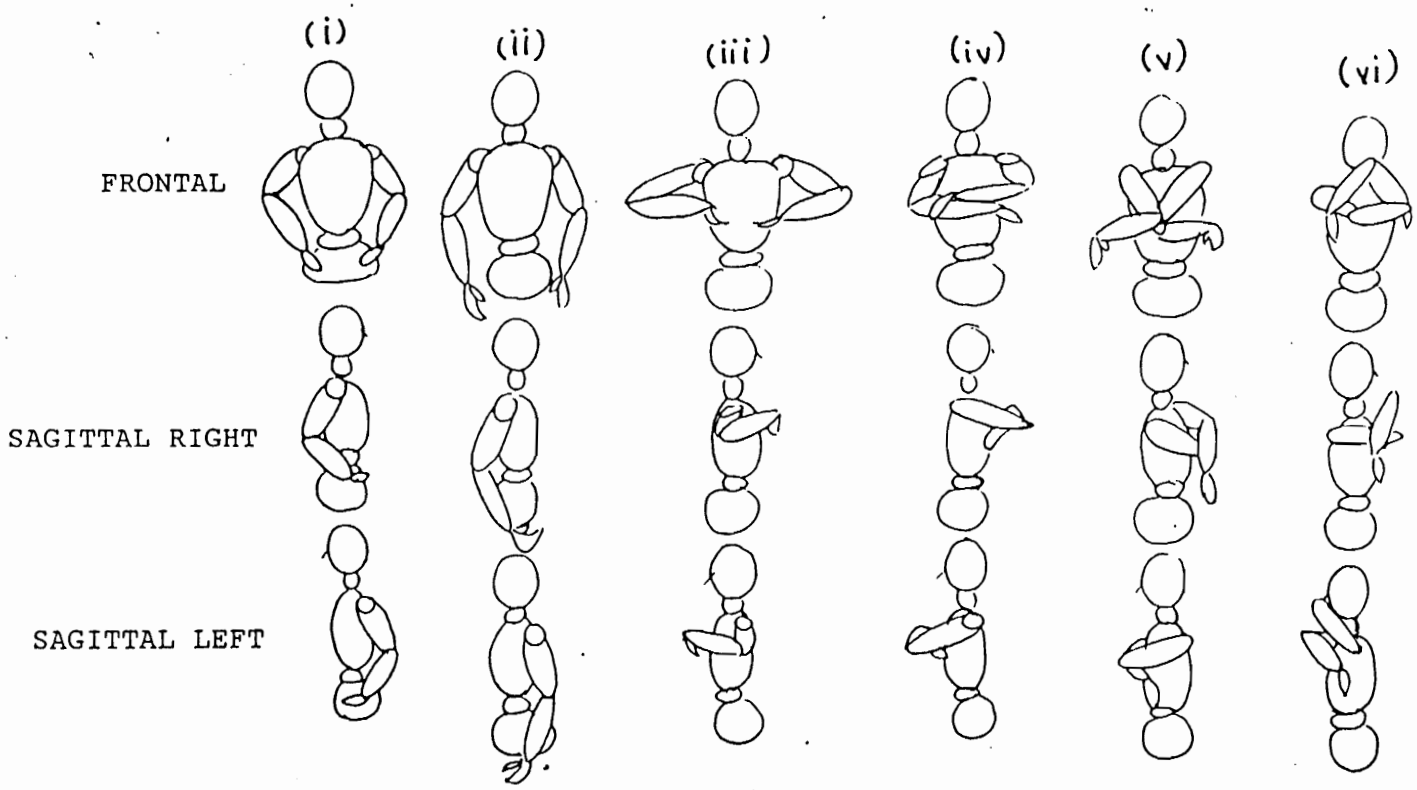
process, therefore interrupted trials were excluded because they were not representative of the doffing process.

On the basis of these criteria, four video films could not be included in the analysis. The starting point of some trials for some views (R001, R017, R019) was missing and so could not be admitted for analysis. The first two trials for doffings of Purchased Garment S were omitted because the garment caught on the subject's glasses in one trial, and the subject lost hold of the garment in the second. The WATSMART data for trial R016 were excluded because IRED 5 became detached from the right shoulder joint and generated false positions for that joint. The absence of WATSMART data for that trial therefore excluded the video trial R016. Data from IREDs which were poorly seen or obscured were also excluded from analysis.

The posterior views of the doffing trials were viewed only to provide information about movements that could not be seen from the front. As the doffing movement included no movements behind the back, the posterior view was excluded from analysis, leaving 30 films (ten each from sagittal left, sagittal right, and frontal views) for each garment available for analysis.

III. OBJECTIVE 1: IDENTIFYING BASIC CRITICAL MOVEMENTS OF THE DOFFING PROCESS

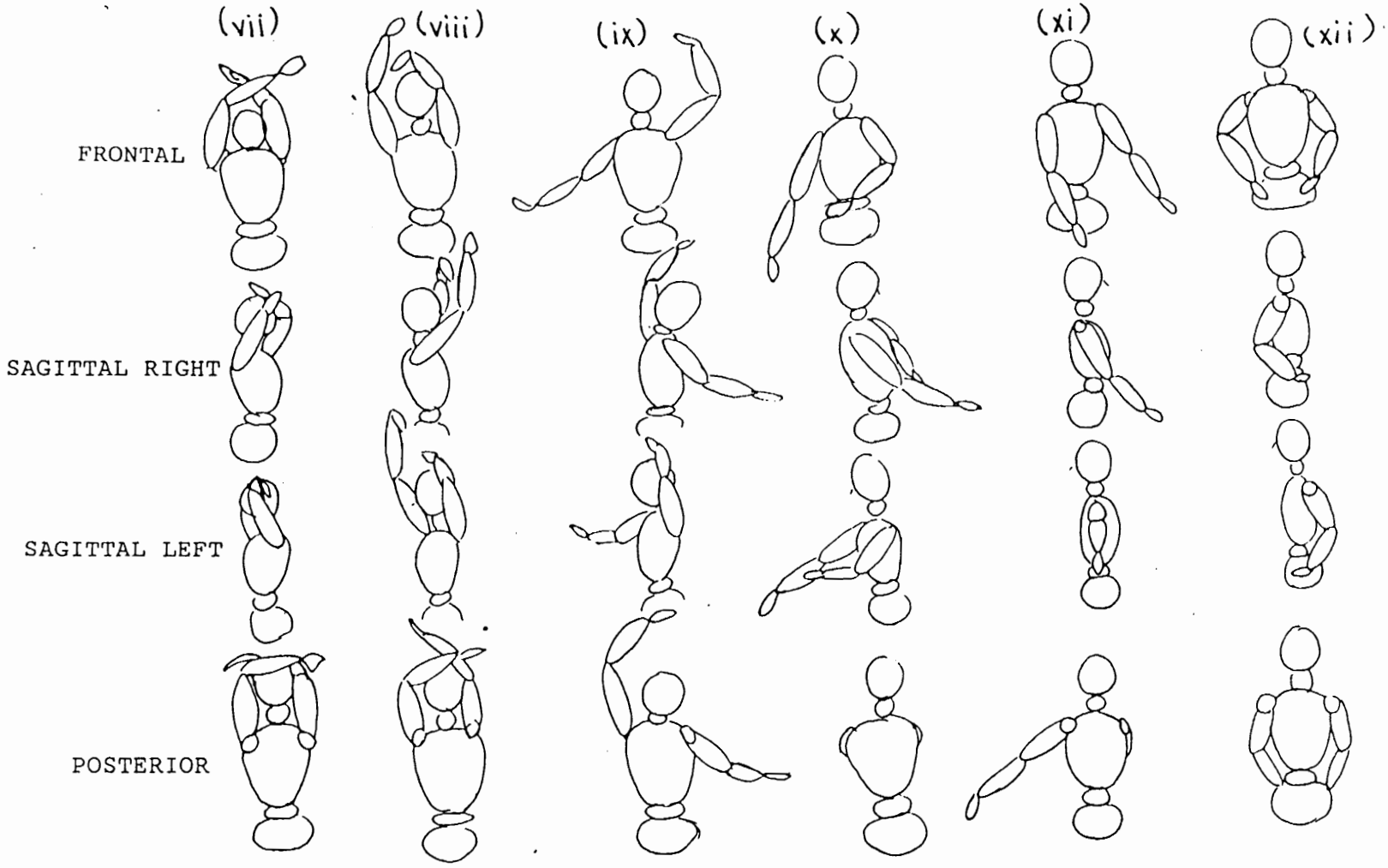
The first objective, to identify the basic critical movements of the doffing process, was addressed by segmental analysis of video films of doffing trials. The twelve identified movements are illustrated in sequence in Figures 13a and b, with each movement assigned a lowercase Roman numeral. Figure 14 illustrates a frontal view of the first ten movements, and also illustrates the garment as it was doffed. The 12 basic movements were classified by Roebuck's terminology. For example, looking at the movement of just the upper arm segment in movement (i) and (ii), since the angle between the upper arm and the torso is decreasing in the frontal plane, the term **frontinvection** would be appropriate. Six of the basic postures were selected to check for



Removal of Garment from the Lower Torso

Removal of Garment from the Upper Torso

Figure 13a
Basic Critical Movements of the Doffing Process



Removal of Garment from the Head, Left Shoulder and Arm

Removal of Garment from the Right Shoulder and Arm

Figure 13b

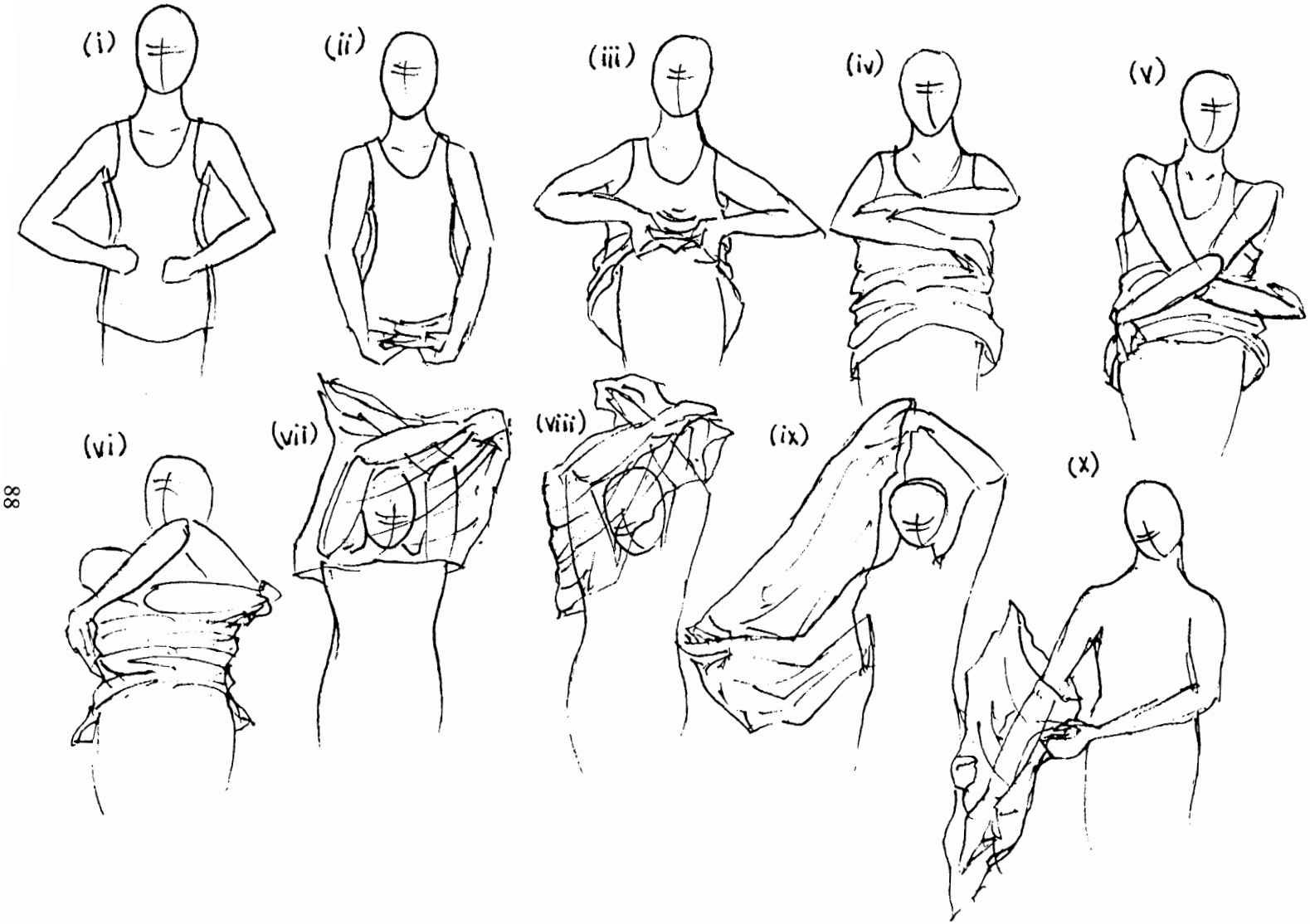


Figure 14
Ten Critical Movements of the Doffing Process Showing Garment

agreement between the video data and the WATSMART data; these are referred to as temporal matching postures.

The twelve movements can be divided into four phases: removal of the garment from the lower torso, removal of the garment from the upper torso, removal of the garment from the head, left shoulder, and arm; and removal of the garment from the right shoulder and arm. The next section describes the doffing process in terms of: 1) position and behavior of the fabric, 2) path of the limb, and 3) spatial orientation of the limb to the body.

III-1. GENERAL DESCRIPTION OF GARMENT DOFFINGS

III-1.1. Removal of the Garment from the Lower Torso

From the starting position (i), doffing began with a bending of the elbow and with the hands positioned at the sides of the garment near the hemline. The fingers gathered the bottom of the garment into folds and pinched them together (ii). The folds were then taken upward to chest level, the arms moving symmetrically (iii). During this phase, the elbows became bent at an acute angle with the upward progress of the movement.

III-1.2. Removal of the Garment from the Upper Torso

When the garment folds reached chest level, the hands released the garment which then lost some of the gathered folds. The forearms crossed rapidly (iv), right arm under left; the hands regrasped the garment, catching as many of the folds as possible (v). The upper arms were crossed so that the elbows were basically in the same vertical axis in front of the body (v). As the arms continued upward, the garment turned inside-out as a consequence of the shoulders of the garment and the hemline of the garment occupying the same horizontal plane. As the arms and the now-inverted garment moved upward, the elbows pointed out from the chest (vi) but continued to move upward as a crossed unit.

III-1.3. Removal of Garment from the Head, Left Shoulder, and Arm

When the garment reached face level, the elbows separated as the upper arms began to uncross (vii). The head dropped forward to the chest (not shown) while the left

upper arm pressed immobile against the face. The left hand released the garment while the right arm began to unbend and the right hand to pull the garment off the left shoulder and arm (viii). To help the right arm pull off the garment, the left arm and head pressed together tightly to reduce tension on the garment.

III-1.4. Removal of the Garment from the Right Shoulder and Arm

The right arm continued to unbend until it was nearly vertical and oriented straight upwards, the hand pulling the garment with it as the arm extended until only the right arm was covered by the garment (viii). As the garment was pulled off the head, the left arm, still in the bent position, began its descent downwards and sidewards; the right arm continued to swing down, still extended straight out (ix). As a purchased garment reached the waistline level, its own momentum helped it slide down and off the right arm, especially the satin garment S. Sometimes the subject leaned forward to increase the propensity for the garment to drop off the right arm. In trials in which the test garments were being doffed, the subject attempted to shake the garment off the right arm. Meanwhile the left arm had reached the same horizontal level as the right arm.

In the case of the long garment, the left arm would cross over to assist removing the right sleeve from the right arm (x) with a raking type motion. The right arm had emerged from the overhead position with the elbow pronated, and as the left arm moved towards it, the right arm supinated. In the case of the left arm assisting the right to shed the garment, the right shoulder retracted backwards and the elbow bent to facilitate the withdrawal of the arm from the garment. Once the right arm was clear of the garment, the left arm swung back to the left side of the body (xi) and dropped the garment on the floor, and then resumed the start position (xii).

In viewing the doffing process in toto, the right upper arm appeared to trace a full circle in the transverse plane, and a semicircle in the sagittal plane. It can be inferred from this observation that the upper arm reached the extremes of its range of motion. This observation is confirmed below in the quantification of the range of motion.

III-2. CLASSIFICATION BY ROEBUCK'S TERMS

The changes in position of limbs during doffing are described below by Roebuck's terminology defined in Appendix C. Roebuck's terms are interpreted by the more commonly known traditional terminology. The movements are referred to by their Roman numerals.

III-2.1. Removal of the Garment from the Lower Torso

From starting position (i) to grasping of the garment (ii), the right and left upper arm frontevected (adduction in the frontal plane), as well as sagevected (extended in the sagittal plane). Concurrently, the right and left forearms frontinvected and saginvected (flexed in the frontal and sagittal planes). The occurrence of a movement in two planes indicated that the movement actually occurred in neither of these planes, but rather a plane in between. From the grasping of the garment (ii) to the raising of the garment to chest level (iii), the right and left upperarms as well as the forearms frontinvected.

III-2.2. Removal of the Garment from the Upper Torso

From their bent position in (iii), the arms crossed over each other at mid-forearm (iv). In this movement, it must be assumed that arm transinvection (horizontal adduction in the transverse plane) occurred since the horizontal level of the upper arms remained the same. The arms continued crossing as they reached over to opposite sides of the body (v), the upper arms frontinvecting to the limit of the shoulder joints' range of motion. As the arms began to move upward (vi), the left and right arm movements were no longer symmetrical, probably because the left arm was overtop the right arm. Both upper arms sagevected from (v) to (vi), but the left arm began sagevecting earlier and at a higher point than the right. It appeared that the forearms did not change from their bent position during the ascent.

III-2.3. Removal of the Garment from the Head, Left Shoulder and Arm

Both upper arms continued sagevecting until they reached the overhead position in (vii). The right forearm frontevected while simultaneously the right upper arm

frontinvected as the garment was drawn off the head (viii); the left arm remained immobile. As the garment left the head, shoulders and left arm, the left upper arm began to frontinvect.

III-2.4. Removal of the Garment from the Right Arm and Shoulder

At this point, both the right and left upper arms were frontinvecting but had different starting points. During the frontinvection of the left arm, the left forearm frontevected to a small extent. As each arm reached waist level, transinvection occurred as the arms moved from the side of the body to the center of the body. The right arm underwent negative frontintorsion (pronation in the frontal plane) as it transinvected. The left forearm negivected, then posivected (flexed then extended) as it pulled the garment off the right arm (x). When the garment was removed from the right arm, the left hand retained hold of the garment. The left arm transevected to drop the garment away from the body while the right arm transevected preparatory to returning to the start position (xi). The right and left arms completed the sequence with forearm frontinvection as the hands returned to the hips (xii).

IV. OBJECTIVE 2: QUANTIFYING THE MOVEMENT PATTERN OF THE DOFFING PROCESS USING WATSMART DATA

The second objective, to quantify the movement pattern, was accomplished by modifying the use of the WATSMART system. The result was a record of the relative angles formed between the line segments connecting the IREDs in certain configurations. The changes in these angles should represent the movement pattern the limbs underwent in performing doffing. The angles were plotted with respect to time. Portions of some traces are missing because 1) an IRED could not be read by the camera because of its location on the body or 2) an IRED was obscured by the movement of a limb. Since the calculation of an angle depends on the existence of data from all three IREDs of a configuration, missing data from any one of the three IREDs means that the angle cannot be calculated.

In this section the WATSMART results for both types of test garment and all doffing trials are presented together. This discussion refers to graphical presentation of WATSMART data. A discussion of the direction of movement depicted by the position vs. time data corresponds to each type of graph. The interpretations that can be made from these graphs are limited to the relative angle as it varies with time; the graphs themselves give no indication of the plane of occurrence, of the trajectory of the limb, nor of the limb's spatial relationship to the body.

IV-1. Left Shoulder Angles

Figure 15 presents a typical graph of the angular displacement vs. time for the left shoulder. Initially the upper arm was held away from the torso, and then distance from the torso decreased, increased, and then decreased again, within the next 1.5 second or so, the net result being an increase in the distance of the upper arm away from the body.

At about 1.5 seconds into the movement, a rapid increase occurred leading to a global maximum for the whole trace of about 150-160 degrees in the shoulder angle could be observed during the time interval 2 - 3.0 seconds. The angle stayed relatively constant for one second, and then decreased rapidly over the next 0.75 seconds to reach its global minimum during the time interval 3.50 - 4.25 seconds. The data are missing for the next period of about 0.50 seconds because the markers were obscured. At about 4.5 seconds after the initiation of the movement it appears that the angle returned to near its original displacement at initiation.

IV-2. Right Shoulder Angles

Figure 16 presents a typical graph of the angular displacement vs. time for the right shoulder. From the start position, the shoulder angle decreases, increases, then decreases for a period of about 1 second. A rapid increase in shoulder angle followed reaching a global maximum of 160-165 degrees during the time interval 2.00 - 2.50 seconds. Almost immediately after peaking, the angle rapidly decreased over the next 1.5

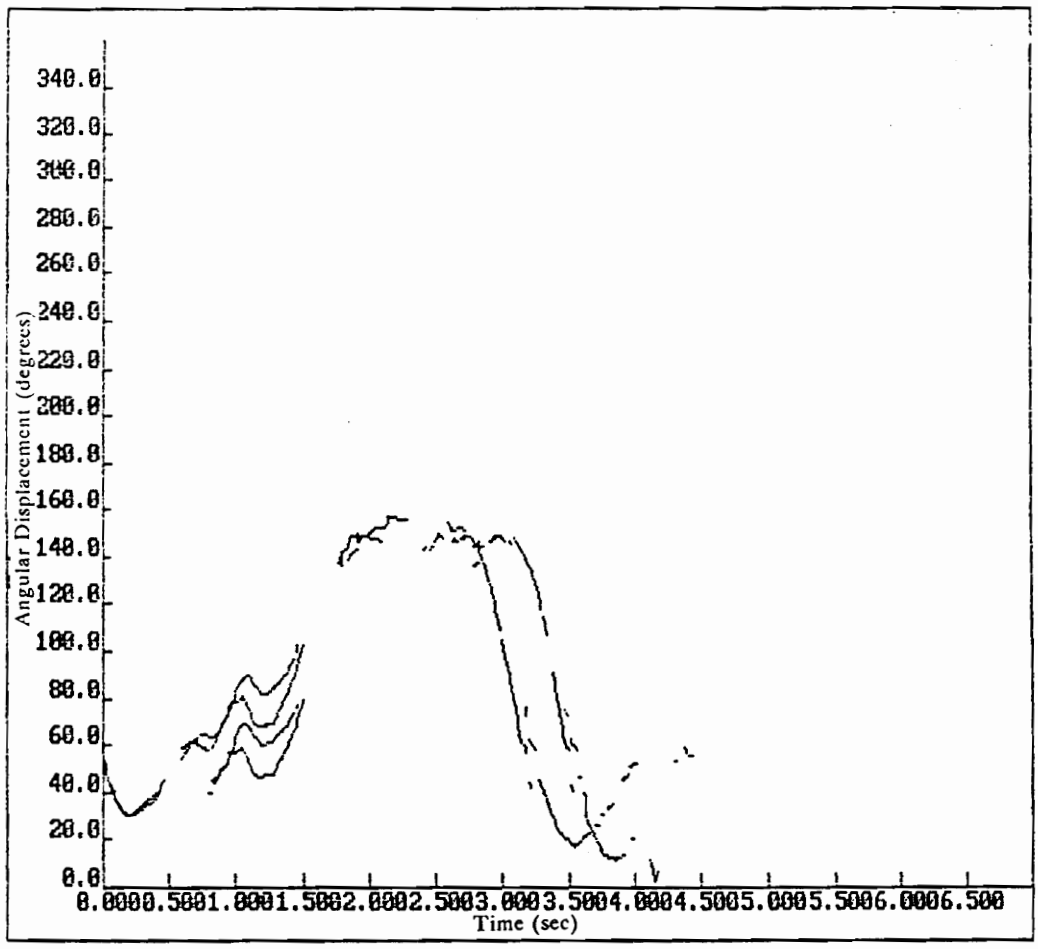


Figure 15
Typical Graph of the Angular Displacement
vs. Time for the Left Shoulder

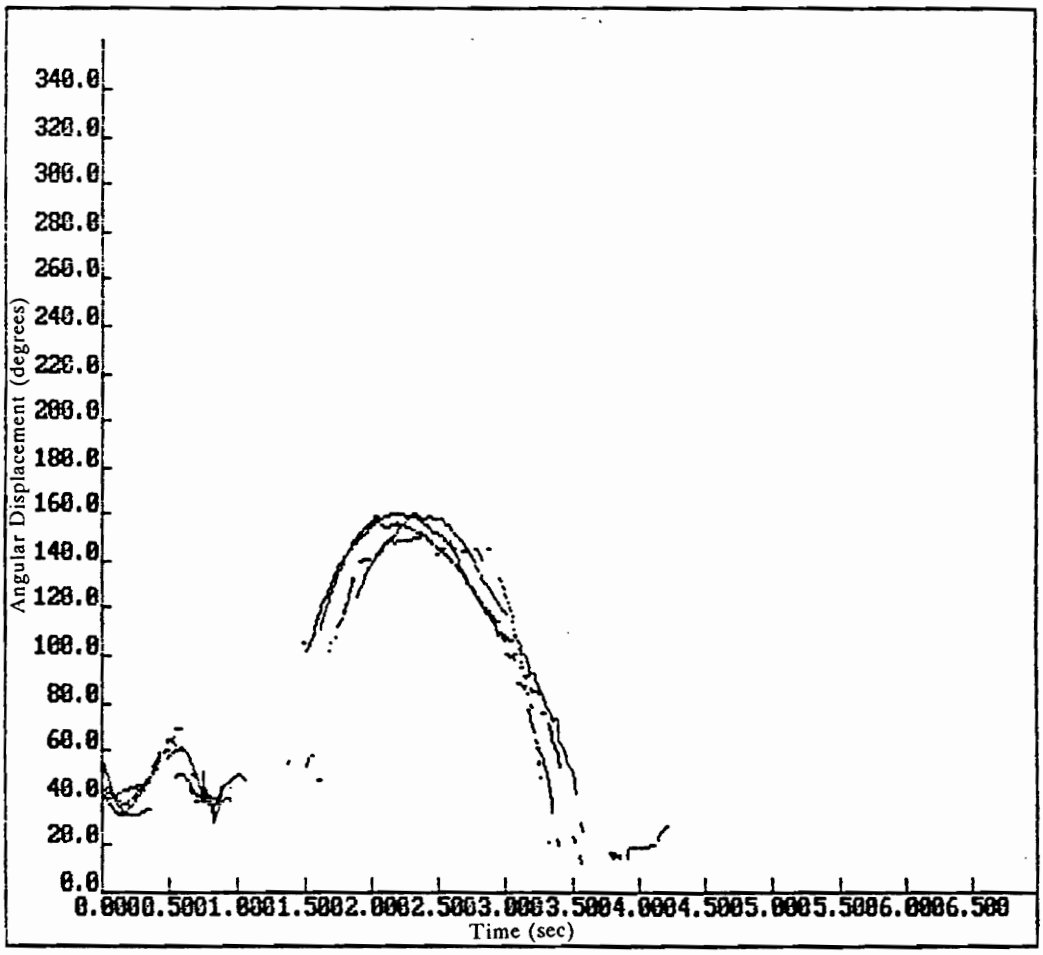


Figure 16
Typical Graph of the Angular Displacement
vs. Time for the Right Shoulder

seconds to bottom out near 0 degrees. For the duration of the movement, data are sparse, but it appears from the little available that the shoulder angle increased again to attain the starting value between 3.5 - 4.5 seconds into the movement.

IV-3. Left Elbow Angles

Figure 17 presents a typical graph of the angular displacement vs. time for the left elbow. The elbow angle fluctuated rapidly for the first second; it quickly increased from the starting point for about 0.25 second, decreased rapidly to reach a global minimum of 0 - 10 degrees in the time interval 0.50 - 1.00 second; then increased and dropped again. The data were then largely missing until the last phase of the movement. The angle reappeared on the traces with a value near 0, and increased rapidly over the next second to reach a global maximum of about 130 degrees in the time interval 3.5 - 4.5 seconds; then decreased slightly but rapidly in the next 0.50 second, and then rose slightly to assume a constant value for the duration of the movement.

IV-4. Right Elbow Angles

Figure 18 presents a typical graph of the angular displacement vs. time for the right elbow. The elbow angle increased a little, decreased, and increased again in the space of 1 second. The data are somewhat scattered for the next 0.50 second, but generally indicated a reduction in angle to a global minimum of 40 degrees in the interval 2.00 - 2.25 seconds. At about 2.5 seconds, the angle gradually increases to reach a global maximum of 160 degrees during the time interval 3.50 - 3.75 seconds. At this point, the data are somewhat erratic, but it appears that the angle stabilizes at about 4.5 seconds at the end of the movement.

V. OBJECTIVE 3: ASSESSING VALIDITY AND RELIABILTY

The third objective was to assess the validity of the method and the reliability of the data. The construct validity of the method was assessed by seeing if the WATSMART data matched the video data, and by determining the degree of simulation and fidelity of the test and purchased garments. Reliability of the data was assessed by examining the

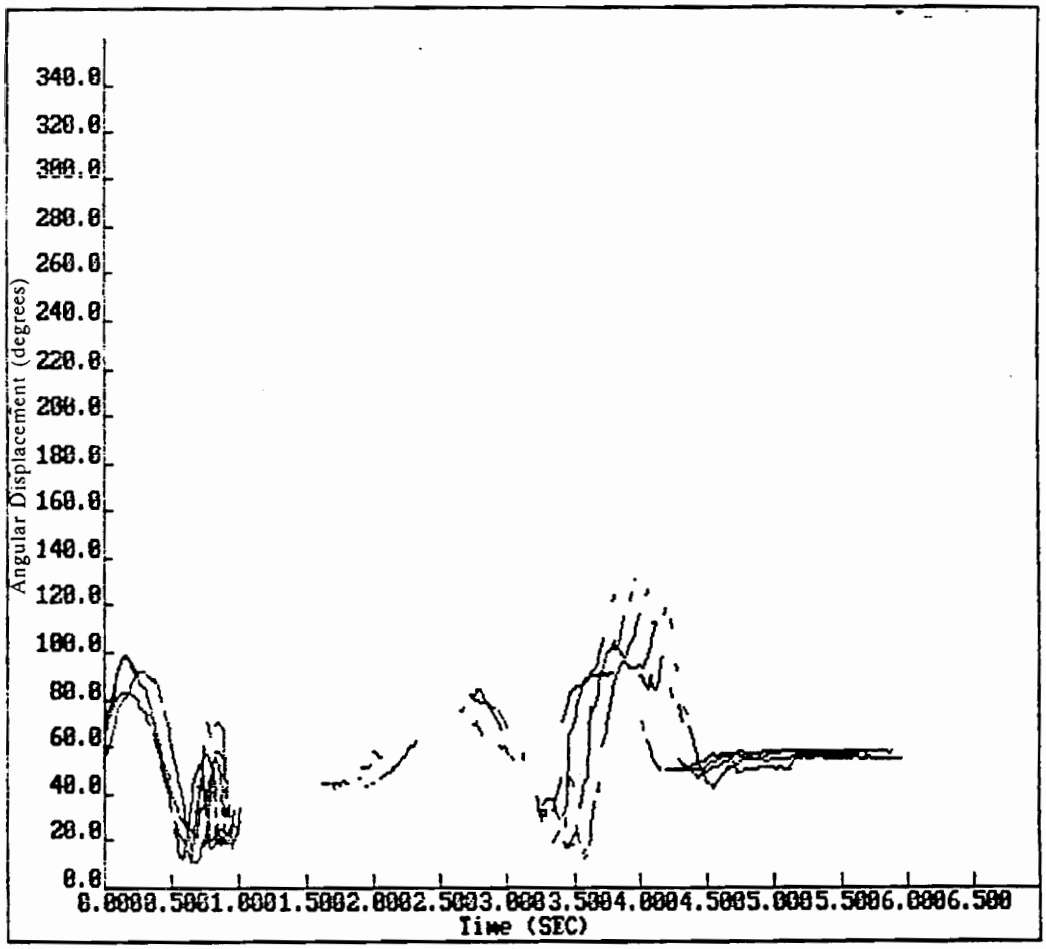


Figure 17
Typical Graph of the Angular Displacement
vs. Time for the Left Elbow

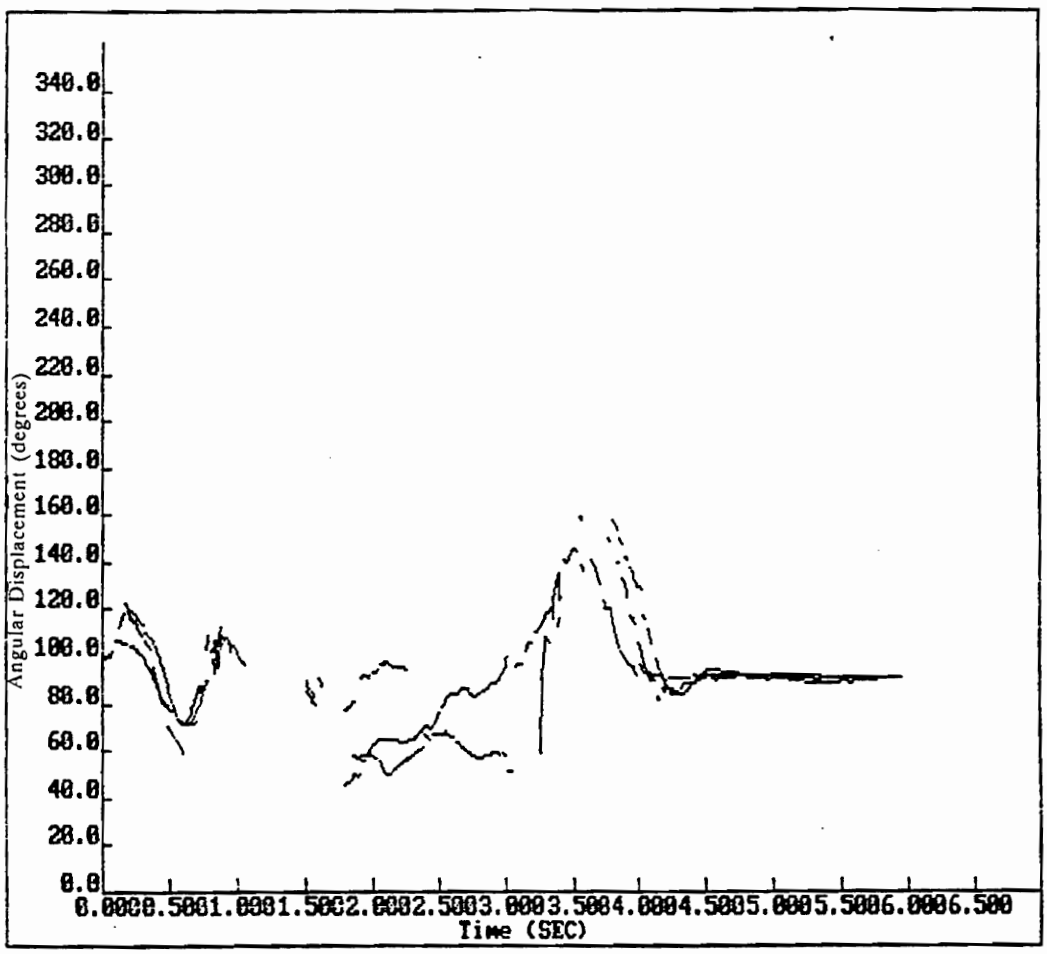


Figure 18
Typical Graph of the Angular Displacement
vs. Time for the Right Elbow

consistency within the WATSMART data. When assessing validity and reliability, the configurations illustrated in Figure 8 will be discussed and described in more detail in this section.

V-1. MATCHING WATSMART POSITION VS TIME DATA WITH VIDEO POSITION VS. TIME DATA FOR TEST GARMENTS

To match the WATSMART data with the video data, both had to be in the same format. The WATSMART data were in the form of relative angular displacement vs. time. The video data were in the form of visual images. The relative angular displacement of the video data was obtained by estimating the position of the limbs in the six temporal matching postures from the video film using the Posture Taxonomy method.

Figure 19 shows a typical charting of one of the temporal matching postures using the PT method. The stick figure at the bottom of the page represents the video image that was being charted. The PT method records postures as the absolute displacement, that is, the deviation from a zero point. The zero point was set at 6 o'clock for this research. Since the WATSMART data were in relative angles, the PT data had to be converted from absolute positions to relative angles. This was done by using simple geometry, specifically, the laws of congruent angles formed by parallel lines. The time of occurrence for each temporal matching posture was determined by counting the number of frames until the movement was attained.

With the WATSMART and video data both in the form of angular displacement vs. time, they could be compared to one another. Tables in Appendix D provide the times of occurrence estimated by the frame counts; Appendix E provides the quantitative data for angular displacement obtained by WATSMART and PT methods; Table 8 presents the average differences. The PT data and the WATSMART data were plotted together on graphs, relative angular displacement on the y-axis, and time on the x-axis. Because the movement was continuously sampled at a high frequency, the WATSMART data are represented by curves. The video data were sampled for only six postures, so these data

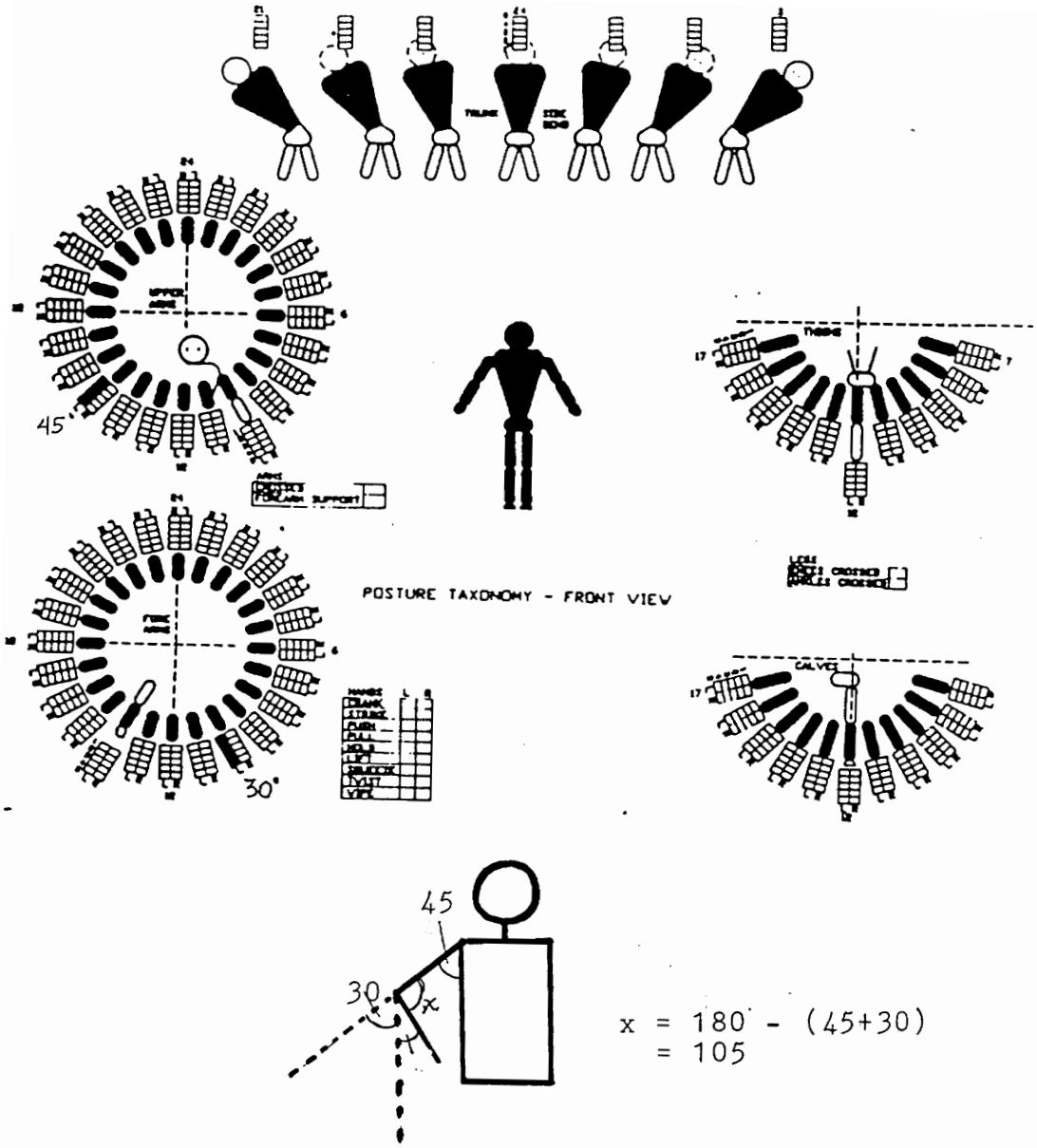


Figure 19
Typical Charting of Position (i) Using PT Method

TABLE 8
Average Differences Between PT Data and WATSMART Data
(in degrees)

Test Garment S				
Posture	Left Shoulder	Right Shoulder	Left Elbow	Right Elbow
i	1.8	2.4	40.6	9.4
ii	10.0	14.8	27.6	29.7
vi	2.7	5.1	n/d	n/d
vii	34.8	30.9	n/d	36.3
viii	24.4	15.1	n/d	n/d
xii	13.3	n/d	32.4	17.5
Test Garment L				
i	2.2	11	40.3	24
ii	13.9	28	58.6	38.2
vi	.6	n/d	n/d	n/d
vii	31.7	46.3	n/d	33.4
viii	28.6	22.3	n/d	n/d
xii	n/d	n/d	16	13.3

are represented by discrete points. The points represent position vs. time data at each temporal matching posture for individual trials. The configuration that best represented the doffing movement was selected and plotted onto a separate graph. This selection was made on the basis of completeness and reasonableness, that is, graphs in which relatively more data was missing than in other graphs, or curves with improbable angular components were rejected. For each trial, the video data were plotted onto WATSMART graphs of the best configurations of IREDs. Figures 20a, b, c, and d show a representative graph of both sets of data for each of the four recorded joints. The PT data are represented by the dots, and the WATSMART data by the curves. Appendix F presents the graphs of trials not illustrated in text.

As is evident from the graphs, there is some agreement, but also some difference between the PT data and the WATSMART data. There are a few reasons for the variation. One reason is that the PT instrument is only precise to 15 degrees, which means that each estimate may be off by as much as 15 degrees. Another reason is that the placement of the hip marker on the front of the body rather than on the side of the body may have resulted in more acute angles being computed by WATSMART for the shoulder than existed in actuality. Probably the most culpable source was that of human error. As indicated by the graphs, the global maximum for the shoulder indicated by the PT data was 180 degrees, about 20 degrees more than that indicated by the WATSMART data. There is evidence (Table 1) that most humans cannot extend the upper arm to that position, but are limited to a maximum extension of about 170 degrees. Another source of error is the assumption that the torso can be approximated as a straight line segment when it is, in fact, two curves; this would affect the resultant shoulder angle. Generally, since most of the error can be attributed to limitations of the PT instrument and the human recorder, and the WATSMART and PT data trace approximately the same pattern, it can be concluded that the WATSMART data describe the same movement as do the video data. The following sections discuss each joint separately in more detail.

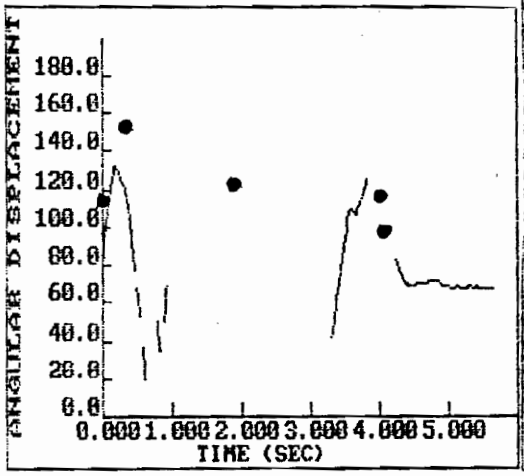


Figure 20a. Left Elbow

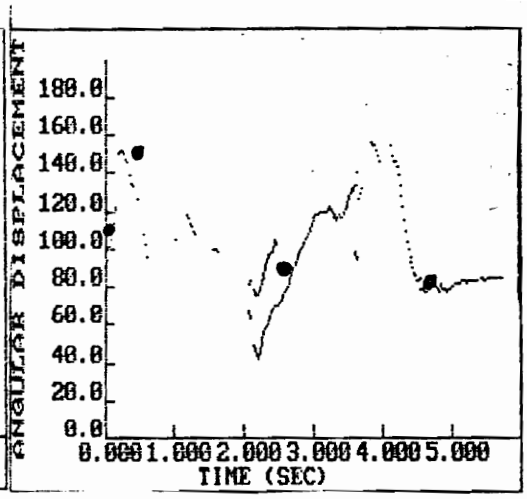


Figure 20b. Right Elbow

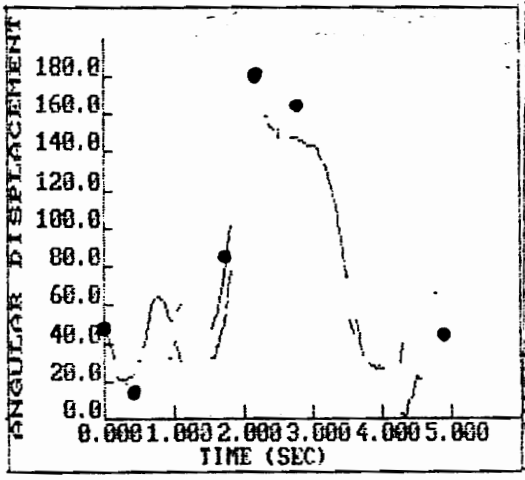


Figure 20c. Left Shoulder

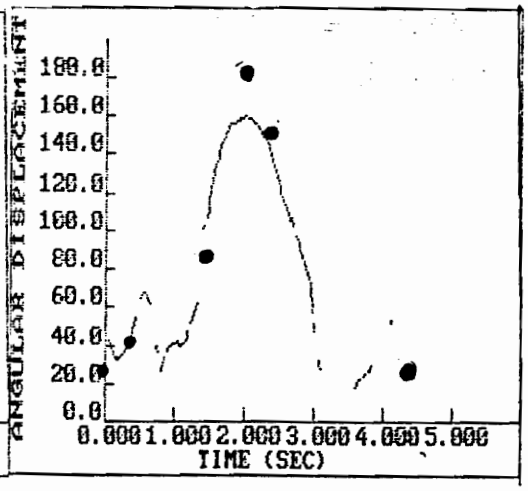


Figure 20d. Right Shoulder

Figure 20
WATSMART Graphs with PT Data at Temporal Matching Postures,
Test Garments, in Representative Trials

V-1.1. Left Shoulder Angle

Tables F1a-1e in Appendix F present temporal matching graphs for the left shoulder. For temporal matching postures (i), (ii), (vii), and (xii) the PT data matched the graph very closely with an average difference of 3 to 10 degrees. PT data for postures (vii) and (viii) were on the average 24 to 34 degrees higher than those of WATSMART.

V-1.2. Right Shoulder Angle

Tables F2a-2e in Appendix F present temporal matching graphs for the right shoulder. The PT data for the right shoulder angle were very similar to those of the WATSMART data with an average difference of 2.4 to 15.1 degrees, with the exception that the PT data for posture (vii) was differed by an average of 30.9 degrees. Possible causes for discrepancies are the same as in the general discussion which precedes the presentation of left shoulder data.

V-1.3. Left Elbow Angle

Tables F3a-3e in Appendix F present temporal matching graphs for the left elbow. The agreement between PT range of motion data and WATSMART position vs. time data is less good than for the other joints. Angular displacements for all postures appeared to be higher in the video data than in the WATSMART data. No conclusion can be made about the match in postures vi, vii, and xii since the WATSMART data are missing at that point. In general, the video data seem to follow the same shape as the graph, but with an average difference of 24 - 40 degrees on the y-axis.

V-1.4. Right Elbow Angle

Tables G4a-4e in Appendix F present temporal matching graphs for the right elbow. There is close correspondence between the video data and the WATSMART graphs for postures (i), (vii) and (xii) although for trials R013 - R015 (Test Garmen L) the beginning of the WATSMART graph was missing. Less correspondence was found for (ii) and (viii). PT estimates for posture (ii) was higher than the WATSMART data by an average difference of 30 degrees. In posture (vii), PT estimates of the angular position

were higher than that of the WATSMART by an average of 36 degrees. No video data could be obtained for posture (vi) and (viii) because the forearm was out of view.

V-2. MATCHING DIRECTION OF MOVEMENT

Another way to see if WATSMART and video data match is to look at the direction of the movement of the limb as determined by the different systems. Roebuck's terminology indicates direction with the lexicons -e- (increasing) and -in- (decreasing). The Posture Taxonomy method indicates direction by a numerical increase or decrease in the angular value. The WATSMART position vs. time graphs indicate direction by the negativity (decrease) or positivity (increase) of the slope. The directions of movement indicated by the above three methods for those temporal matching postures which were consecutive are compared in Table 9. The comparison shows that for the right shoulder, the right elbow, and the left shoulder, the direction indicated by the three methods is the same when observable (all but one case). The data are too incomplete for the left elbow to make a definitive statement.

Because there appeared to be fairly good correspondence between the video position/time data and the WATSMART position/time data, and between the direction of movement obtained by video analysis and that obtained from WATSMART graphs, it can be concluded that the data from different sources converge on the same construct, namely, the doffing movement.

V-3. DEGREE OF SIMULATION AND FIDELITY BETWEEN THE PURCHASED GARMENTS AND THE TEST GARMENTS

The last way to assess the convergence of the data was to assess the degree of simulation and fidelity between the test and purchased garments. The degree of simulation is how much the simulation looks like the original; the degree of fidelity is how much the simulation acts like the original. The degree of simulation was good because the construction and appearance were preserved by exactly replicating the pattern pieces of the original garments for duplication in test fabric. The degree of fidelity was

TABLE 9
Comparison of Angular Directions Between Test and Purchased Garments and WATSMART Data

	i-ii	vi-vii	vii-viii
Right Shoulder			
Roebuck	-	+	-
Posture Taxonomy	-	+	-
WATSMART	-	+	-
Right Elbow			
Roebuck	+	+	+
Posture Taxonomy	+	o	+
WATSMART	+	+	+
Left Shoulder			
Roebuck	-	+	-
Posture Taxonomy	-	+	-
WATSMART	-	+	-
Left Elbow			
Roebuck	+	o	o
Posture Taxonomy	+	o	o
WATSMART	+	+	-

+ indicates increase, - indicates decrease, o indicates no change observable

compromised, however, by the difference in fabric properties between the purchased and test fabrics. The direction of the movements was the same as were the sequence and type of the movements based on comparison of Posture Taxonomy chartings, WATSMART graphs, and Roebuck's terminology.

The average of the cumulative total time taken to doff each type of garment was calculated. The mean for Test Garment S was based on ten observations, while that for Test Garment L was based on only nine since trial R017 was omitted. The means for Purchased Garments S and L were based on two observations, two trials having been omitted due to interference from external sources. The small number of trials for these garments was considered to be sufficient since these doffings immediately followed 20 trials of test doffings, establishing a constant level of skill. In an attempt to explain this observation, Figures 21a and b presents the mean times of occurrence of eeach posture for each type of garment. The valus for posture (xii) reflects the total mean time to doff.

The time of occurrence of the movements varied, however, as shown by Table 10. Times of occurrence are presented for the left and right arms since they did not always perform symmetrically. Some preliminary explanations are offered to explain the differences in the time values, but a post-hoc test, such as a Duncan's test, would be necessary to validate the explanations. The attainment of postures (ii) and (viii) appeared to be similar among the test and purchased garments (the data were missing for Purchased Garment L), but diverged for (vi), (vii), and (xii). Purchased Garment L attained postures (vi) and (vii) last but Test Garment L attained (vi) earlier than Purchased Garment L, and (vii) earlier than both Test Garment S and Purchased Garment S. This seems to eliminate the dimensions of style L as a factor, and to implicate the fabric type as the culprit. The total time to doff for Purchased Garment L was less than that for Test Garment L on the average, however; so the test garment appeared to have surpassed that of the purchased garment during posture (viii), but this cannot be confirmed since the time data could not be ascertained since the more opaque purchased garment obscured the limbs. The

TABLE 10
Cumulative Mean Doffing Times for Test and Purchased Garments by Temporal Matching Posture

Table 10a. Cumulative Mean Doffing Times by Posture Sequence
Test Garments

	Test Garment S		Test Garment L	
	Left Arm	Right Arm	Left Arm	Right Arm
ii	0.328	0.328	0.379	0.379
vi	1.44	1.55	1.61	1.75
vii	2.26	2.09	2.06	2.07
viii	2.51	2.49	2.63	2.55
xii	4.49	4.49	4.63	4.63

Table 10b. Cumulative Mean Doffing Times by Posture Sequence
Purchased Garments

	Purchased Garment S		Purchased Garment L	
	Left Side	Right Side	Left Side	Right Side
ii	0.349	0.349	0.287	0.287
vi	1.67	1.65	1.94	2.11
vii	2.06	2.06	2.68	5.68
viii	2.49	2.48	n/d	n/d
xii	3.18	3.18	4.18	4.18

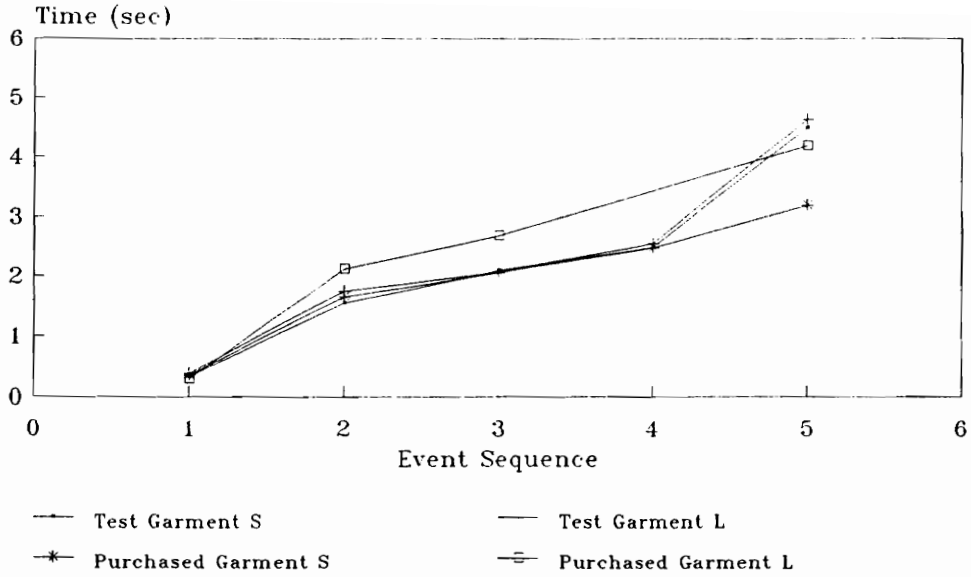


Figure 21a
Time of Occurrence of Postures
(Right Side)

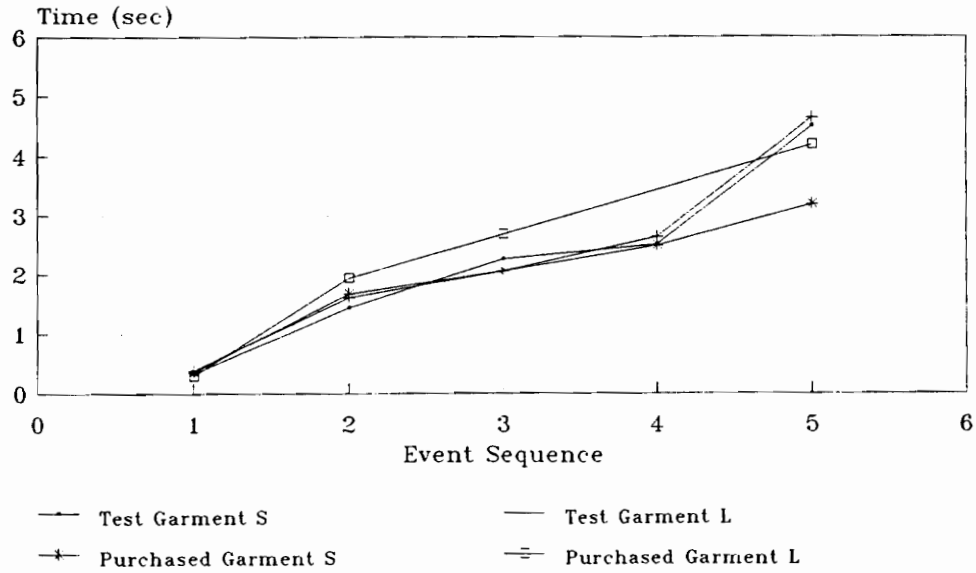


Figure 21b
Time of Occurrence of Postures
(Left Side)

purchased garments did appear to require less effort to remove from the right arm at the end of the movement (xii), the garments falling down rather than needing to be pulled down. This might be because the test fabric seemed to cling to the body more than that of either of the purchased garments while the subject was pulling the garment up. This clinginess also appeared to allow the test garments to maintain the gathered folds longer than the purchased garments, seemingly requiring less energy and speed to regrasp them, which might explain why Purchased Garments S and L respectively attained posture (vi) slower than Test Garments S and L.

The overall appearance of the movements also differed in that the angular displacement of the right arm as it extended over the head was apparently greater in the purchased garments than for the test garments. The cause for this is not clear: it could be due to the wiring of the IREDs on the subject, or it could be due to a difference in fabric properties. The effect of fabric properties is discussed in some detail in the next section (VI-1). Another difference was in the shedding of the right sleeve of Garment L; in the test garments, the sleeve had to be pulled off, whereas in the purchased garments, the sleeve slid off unassisted.

Despite the similarity in direction and sequence of movements, the differences in the times to doff and the difference in the removal of the right sleeve, as well as the effect of the wiring in the test situation, need to be further evaluated before a definitive statement can be made as to the degree of fidelity between the test and purchased garments.

V-3.1. Possible Effects of Fabric Properties and Garment Dimensions on the Degree of Fidelity

Differences in the recorded times in the doffing trials were speculated to be associated with 1) an attempt to reduce the length of the garment and 2) extra effort needed to remove the long sleeve of garment L. The behavior of the fabric while being manipulated is a function of not only garment dimensions but also various fabric

properties. To explore the possible effect of various fabric properties and garment length on the doffing process, graphs were made plotting each of several fabric variable and each of three garment dimensions against the total mean time needed to doff each garment type (Figures 22a - j). These findings are included to stimulate hypotheses about the effect of fabric properties on movement in general, but should not be used to make definitive statements about the phenomena observed in this research, nor in any other. The limited nature of this analysis precludes any generalizations of the findings.

The fabric properties treated were flexural rigidity, thickness, weight, cover factor, stretch, immediate growth, static growth; the garment dimensions studied were neck-to-hemline length, sleeve length, and armscye depth. Table 7 presented the values obtained for each of these properties. The results of this simple graphical analysis suggest that mean time to doff is positively related to fabric stiffness, thickness, stretch, immediate growth, static growth, and neck-to-hemline length, and is negatively related to cover factor, weight, and armscye depth.

These results seem to support speculations made previously in the literature. A stiff and/or thick fabric may not be as easily compressible as a more flexible and thin one, and so may require more time to manipulate it (Watkins, 1984). The effect of fabric extensibility may also alter the ability of the human to move his own limbs to doff the garment by restricting the movement of the skin over the joint (Kirk & Ibrahim, 1966). A longer neck-to-hemline length requires more effort to gather the excess length and maintain those gathers at a manageable level.

At first glance, the finding that more weight is associated with less time to doff may seem to contradict the study of Adams and Keyserling (1991), as well as common sense. For a task of short duration, like doffing, weight is likely to offer little impedance according to Adams and Keyserling (1991) and the momentum generated by more mass may actually help the garment drop off the right arm in the final stage. The effect of cover factor might create air resistance due to the interstices between yarns. A longer

FIGURE 22
Fabric/Garment Properties by Mean
Total Doffing Time

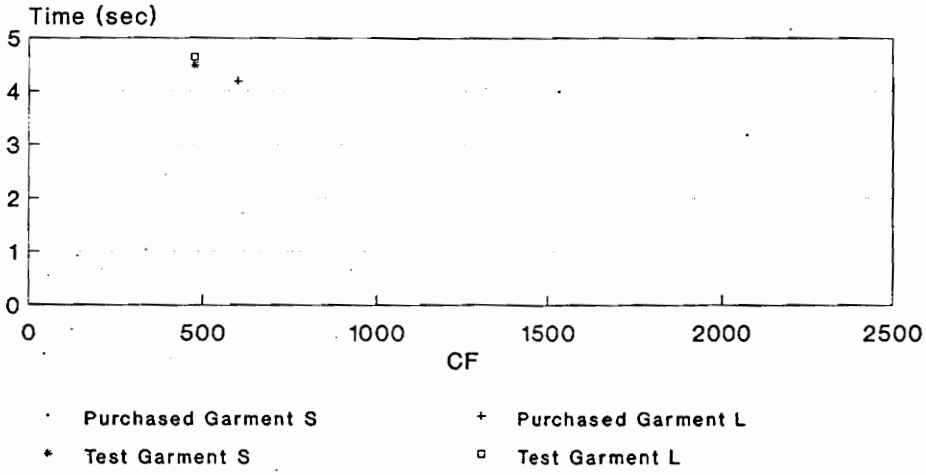


Figure 22a
Total Mean Doffing Time
vs. Cover Factor (CF)

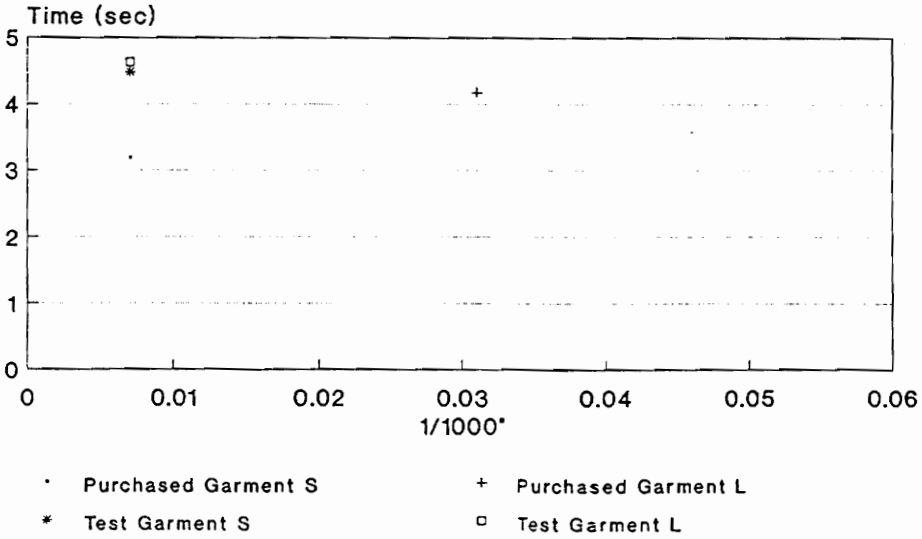


Figure 22b
Total Mean Doffing Time
vs. Fabric Thickness

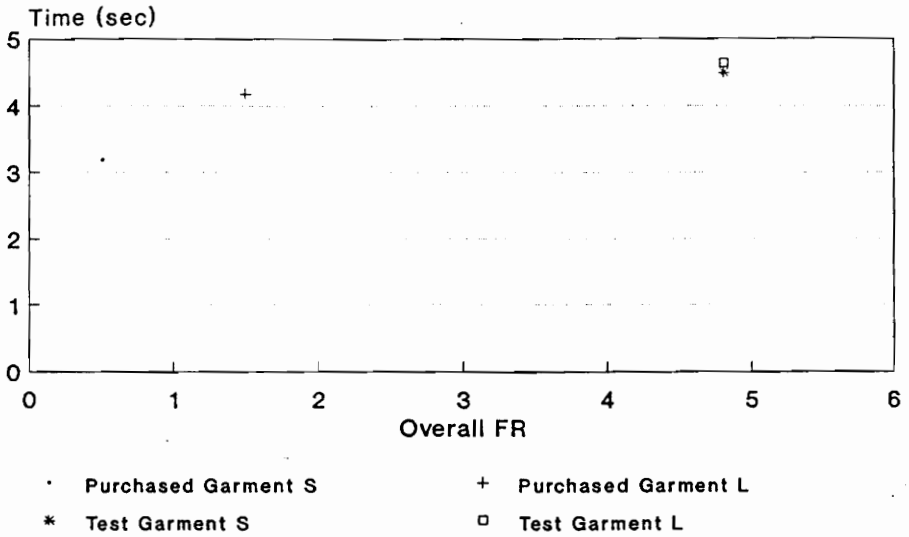


Figure 22c
Total Mean Doffing Time
vs. Flexural Rigidity (FR)

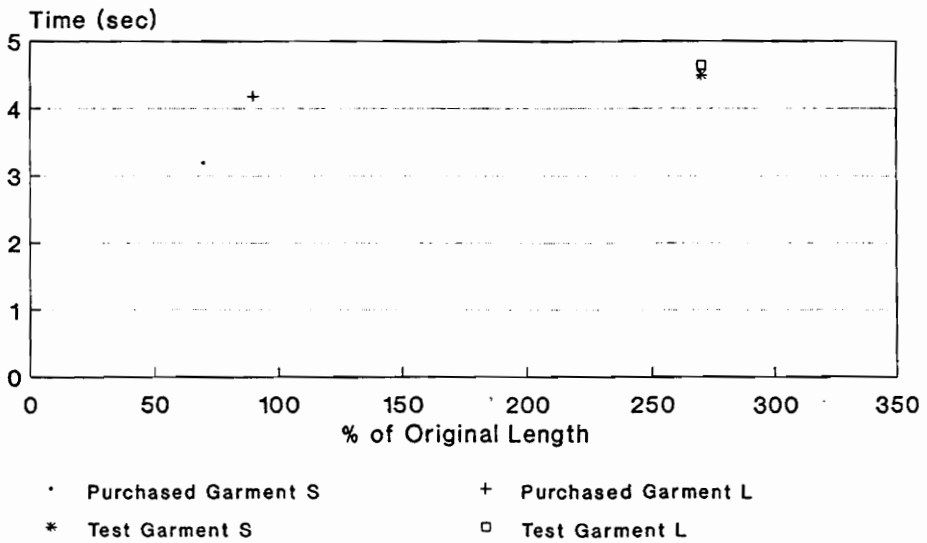


Figure 22d
Total Mean Doffing Time
vs. Fabric Stretch

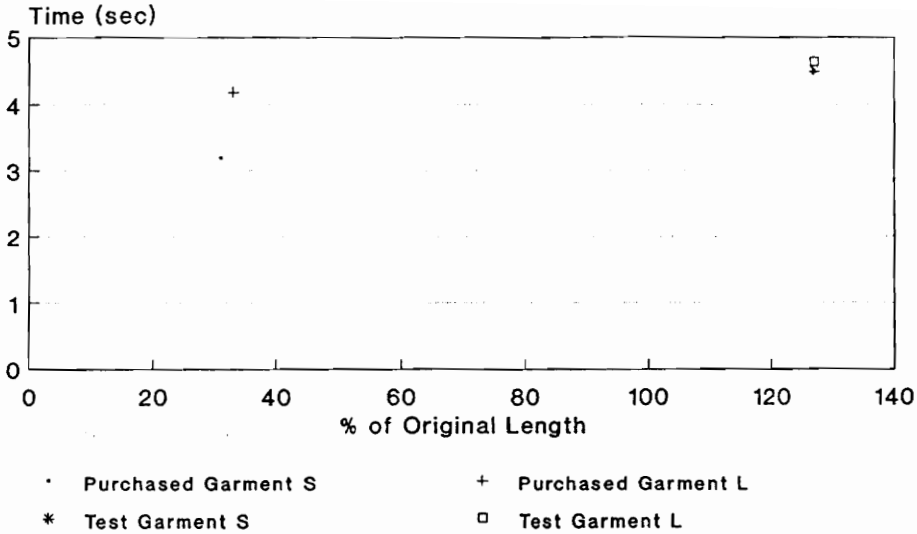


Figure 22e
Total Mean Doffing Time vs.
Immediate Fabric Growth

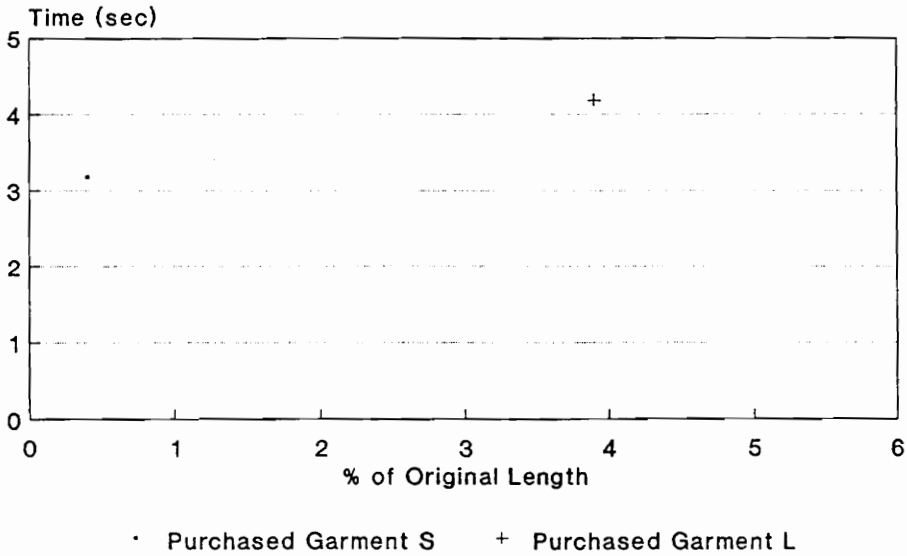


Figure 22f
Total Mean Doffing Time vs.
Static Fabric Growth

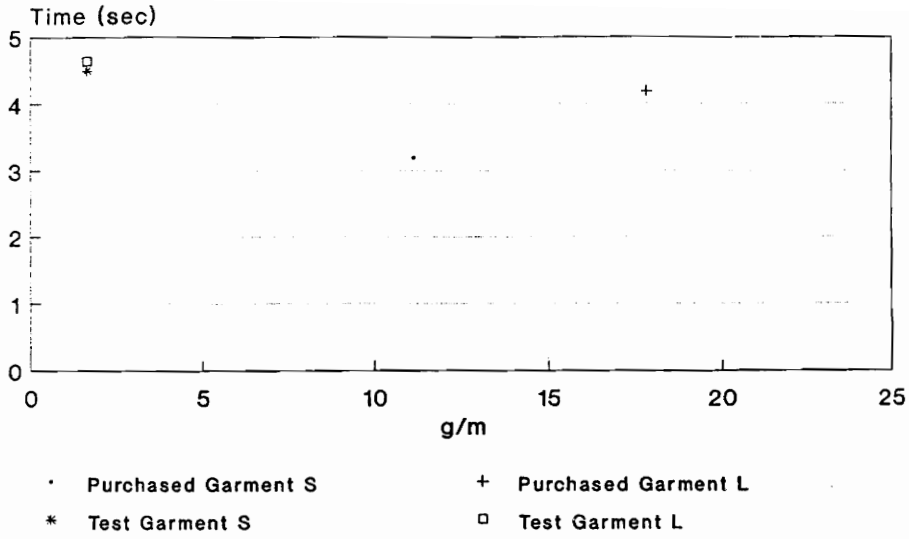


Figure 22g
Total Mean Doffing Time
vs. Fabric Weight

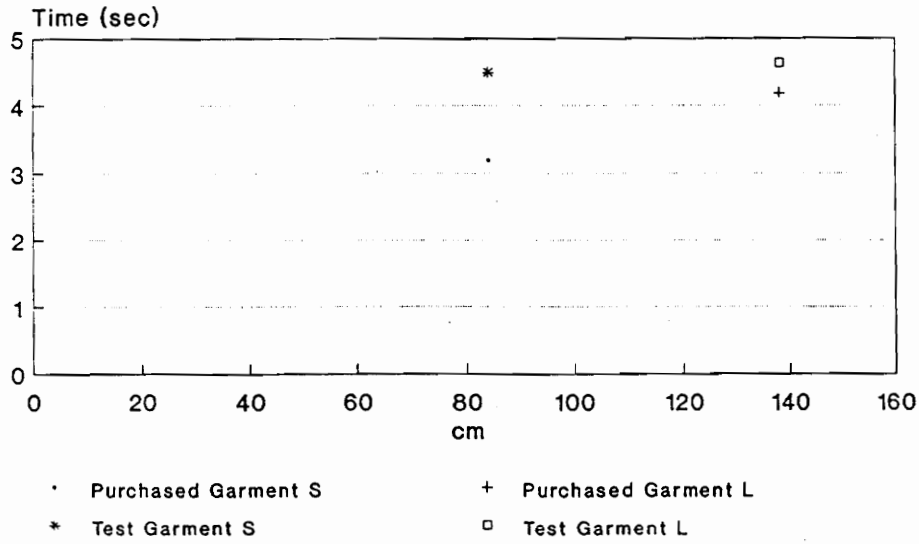


Figure 22h
Total Mean Doffing Time
vs. Garment Length

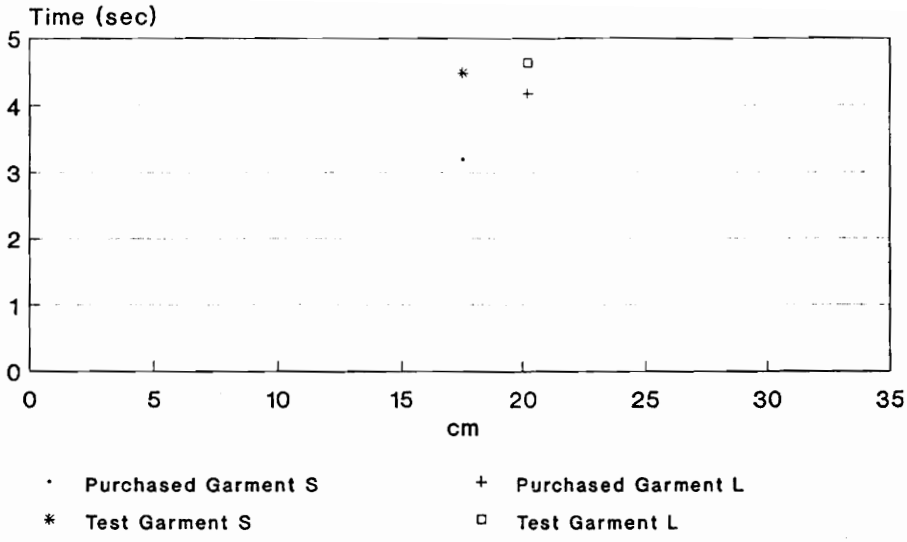


Figure 22i
Total Mean Doffing Time
vs. Armscye Depth

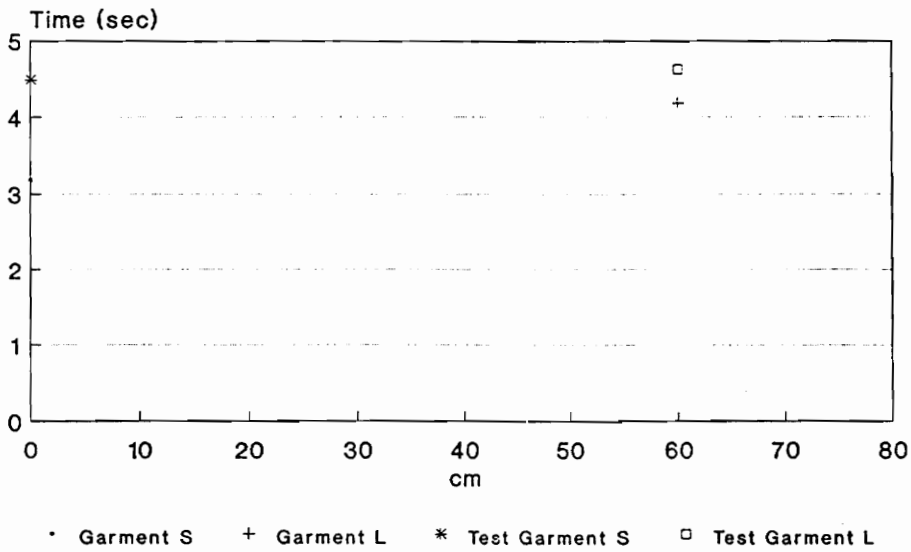


Figure 22j
Total Mean Doffing Time
vs. Sleeve Length

armscye depth would seemingly allow freer movement of the shoulder girdle, but if bounded by a sleeve, may induce the hobbling effect.

V-4. OBJECTIVE 3: ASSESSING THE RELIABILITY OF THE DATA

The second part of objective three was to assess the reliability of the data. According to Kerlinger (1974) reliability is based on two components: accuracy and consistency. To look at the accuracy of data, one must presume the existence of a "true" set of data to compare against. As was established earlier, there is no "true" set of data describing the doffing movement in quantitative or qualitative terms, so accuracy cannot be addressed in this study. Consistency, however, can be assessed. This study looked at the consistency within trials (intra-trial consistency) and the consistency between trials i.e., the consistency of the subject's performance.

V-4.1. Consistency of WATSMART Data Across IRED Configurations

Intra-trial consistency was assessed by plotting different configurations of IREDs for the same trials on one graph incoproated with the text. Figure 12 illustrated how the different configurations of IREDs for each joint can result in different values for the same joint angle. Figure 8 is repeated here in Figure 23 so that the reader may see the various configurations of markers referred to by the text. Figures depict typical graphs of different marker configurations for respective joint angles. Appendix H provides graphs for all trials recorded. On each figure, there is more than one curve describing the movement of the joint. These different curves represent the different configurations of IREDs on the body. Different configurations of IREDs which describe the same joint are possible because most joints were identified at different bony landmarks. The angular displacement for many of the graphs varied by as much as 20 degrees from configuration to configuration. This points out the error in the assumption that the same angular value would result regardless of where the markers were put.

Left Shoulder Angles. Figure 24 shows a typical plot for the left shoulder. Three configurations of IREDs of the left shoulder are shown:

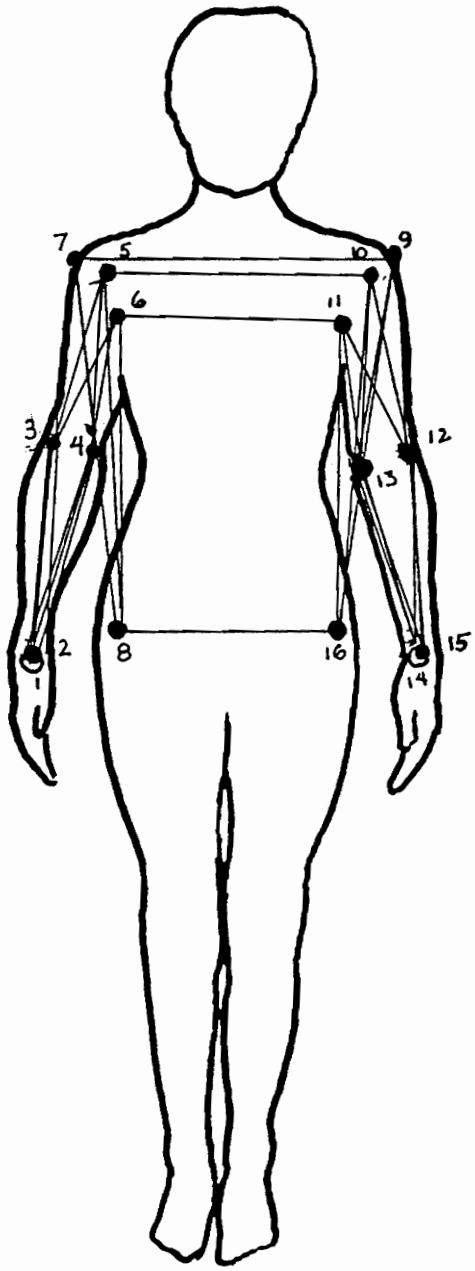


Figure 23

Repeat of Figure 8

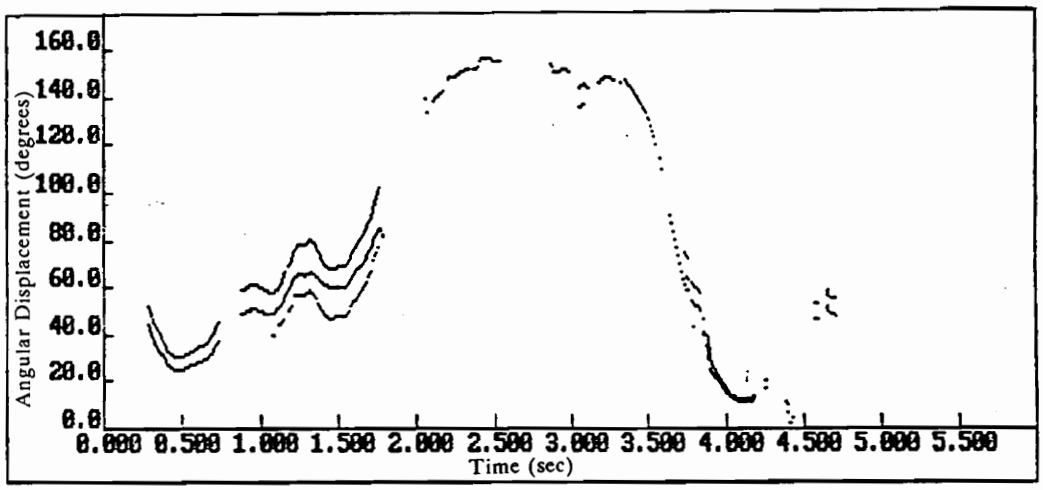


Figure 24
Typical Intra-Trial Consistency Graph for Left Shoulder

Configuration 1: 3, 5, 8
Configuration 2: 4, 5, 8
Configuration 3: 3, 6, 8

Plots of configurations of IREDs for the left shoulder joint look very similar, indicating that they depict the same movement pattern. There is, however, a spread of about 20 degrees between the traces, which indicates that each configuration approximated the angle differently. This difference is directly attributable to the difference in configuration of the IREDs on the body and is readily seen on Figure 23. The angle formed by the line segments linking IREDs 8, 6, and 4 is more acute than that formed by IREDs 8, 5, and 3. The combination of configurations that agreed most with the PT estimates of angular displacement and that most completely reflected the movement of the shoulder were the traces for configurations 1 and 2.

Right Shoulder Angles. Four configurations of IREDs were possible to describe the movement of the right shoulder, but only two appeared to reflect the movement of the right shoulder most completely. Figure 25 shows a typical graph of two configurations of IREDs of the right shoulder:

Configuration 1: 12, 10, 16
Configuration 2: 13, 12, 16

There appears to be a spread of about 15 degrees between traces of different IRED configurations. The difference in the angles formed by the different configuration of IREDs explains this variation.

Left Elbow Angles. Eight configurations of IREDs were possible to describe the left elbow angle, but because IRED 1 was not visible throughout the movement, only four configurations were usable for analysis. Of these four, only two configurations were found to represent the movement most completely:

Configuration 1: 2, 3, 5
Configuration 2: 2, 3, 6

Figure 26 shows a typical graph of these configurations for the left elbow. The traces differed by about 20 degrees. Configuration 1 appeared to agree most with PT data of the

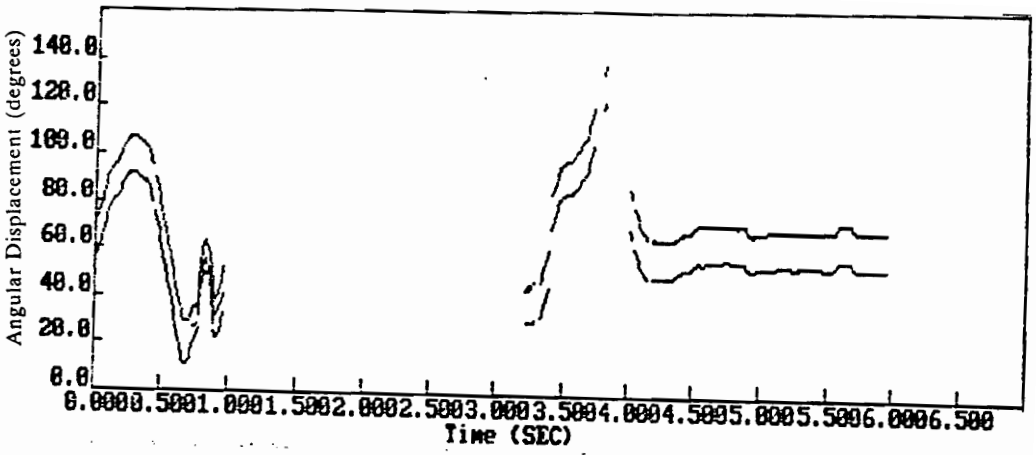


Figure 26
Typical Intra-Trial Consistency Graph for the Left Elbow

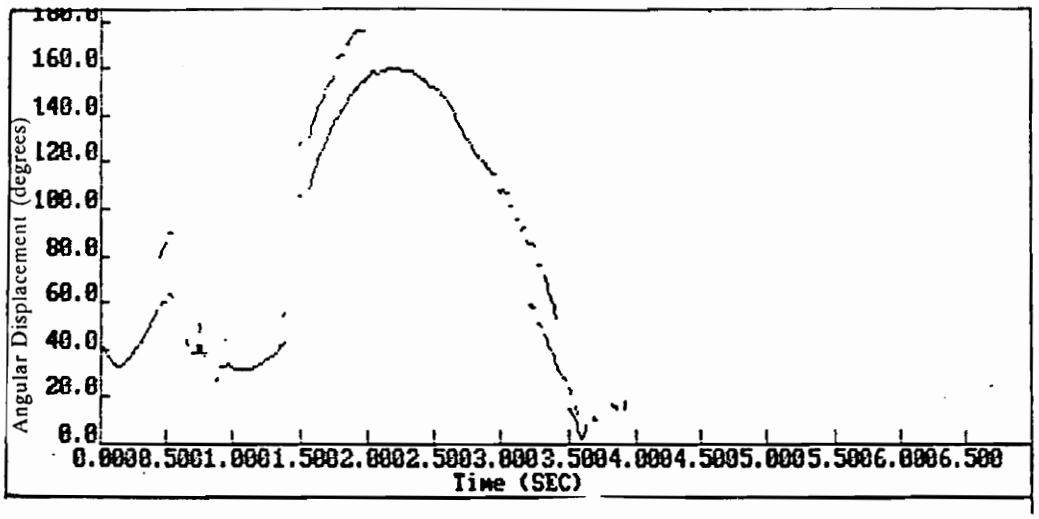


Figure 25
Typical Intra-Trial Consistency Graph for the Right Shoulder

two, although both configurations possessed the same degree of completeness. The traces are remarkably similar, indicating that the same movement was recorded in each.

Right Elbow Angles. Eight configurations of IREDs were possible to describe the right shoulder angle, but only three appeared to reflect the movement of the right shoulder most completely. Figure 27 shows a typical graph of these two configurations of IREDs of the right elbow:

Configuration 1: 13, 11, 14
Configuration 2: 12, 10, 15

It appears that the configurations of IREDs are measuring the same movement, but the sections where the data are sporadic make it difficult to assess the degree of consistency. A maximum of 20 degrees separates the two traces.

V-4.2. Consistency of the Subject's Performance in Doffing

The inter-trial consistency, that is, the variability between trials, is really a measure of the consistency of the performance of the subject from trial to trial. For each garment, traces of the "best" configuration of IREDs for each trial were plotted on the same graph. Figure 28 depicts typical inter-trial consistency graphs for the four joints, and Appendix I presents graphs for all trials recorded. The traces for the left and right shoulder angles were fairly similar in the sequence and magnitude of angular displacement, but the times of occurrence varied somewhat by as much as 0.75 seconds. This variation was not considered to be an indication of a different movement was taking place, but rather evidence of the natural variability of human performance. As trials progressed, the time to doff increased, suggesting that the subject may have become fatigued. The left and right elbow traces indicated that a different movement took place in some trials. For the left elbow, the graphs appeared to be very consistent for the first part of the movement, but less consistent for the later half. In particular, trials R001 and R002 showed a different left elbow movement for this later portion compared to the other trials. Reviewing the video films for those trials, the left elbow was behaving differently

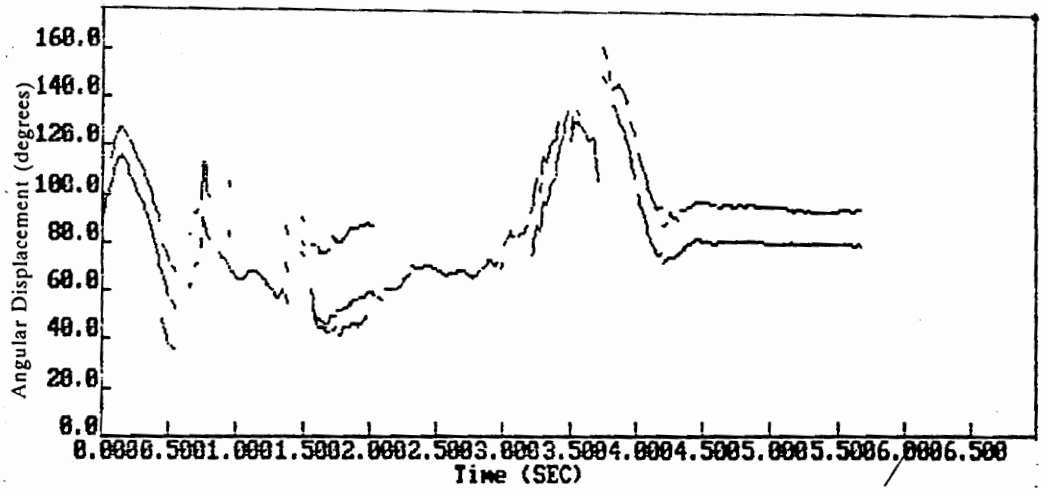
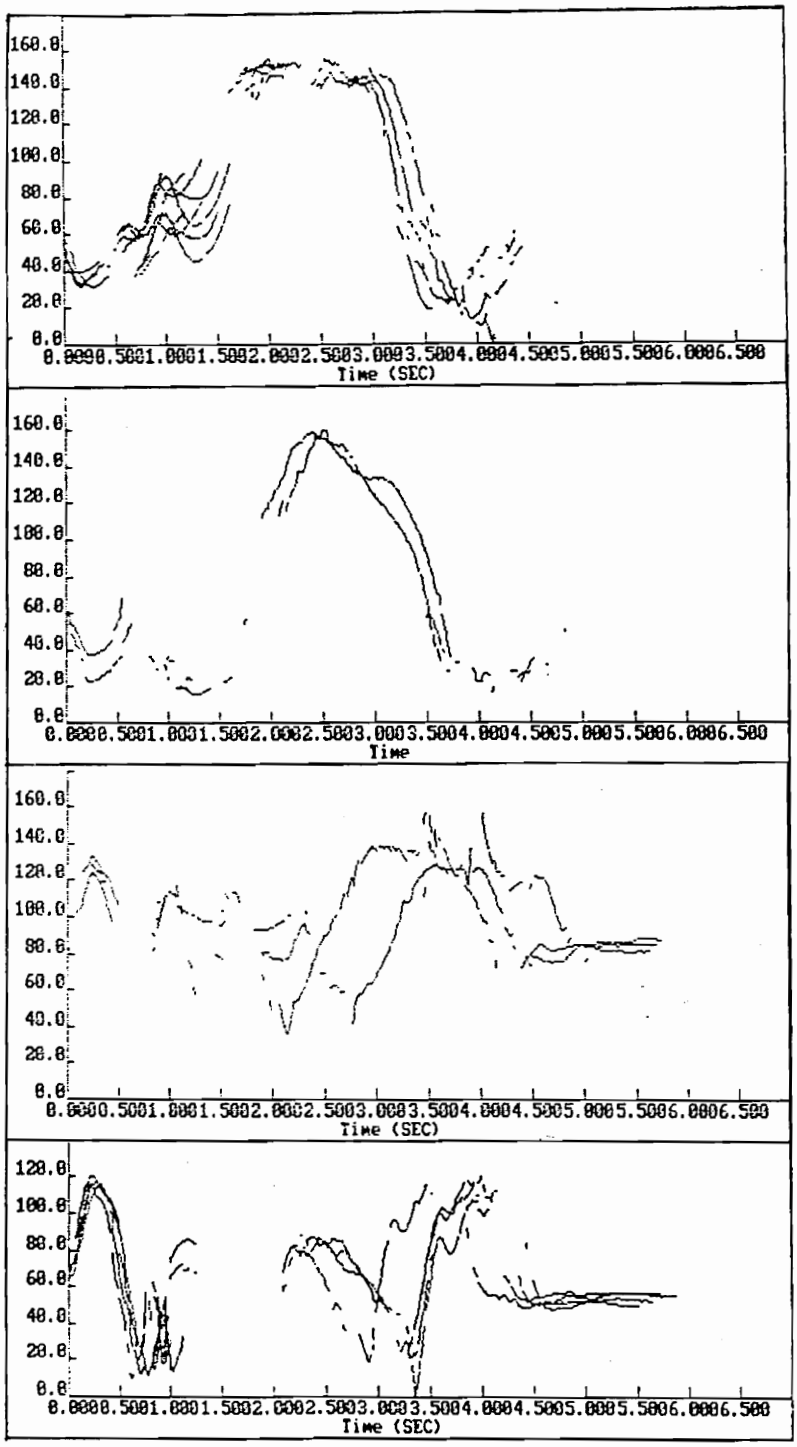


Figure 27
Typical Intra-Trial Consistency Graph for the Right Elbow



(a) Left Shoulder

(b) Right Shoulder

(c) Right Elbow

(d) Left Elbow

Figure 28
Typical Inter-Trial Consistency Graphs

than in the other trials; in other trials, it appeared to assist removal of the garment, whereas in trials R001 and R002 the right arm tried to shake off the garment. For the right elbow, the graphs appeared to be roughly consistent for the first part of the movement, but less consistent for the later half. The slope of the graphs, their overall shapes, and the peaks display some variation. The variation in the graphs for the second half of the motion can be attributed to the final removal of the right sleeve. It was noted above that the subject removed both types of garments from the right arm in three ways (shaking, sliding, and pulling) which required different actions of the forearm.

V-4.3. Variability of the Data Between Garment Styles S and L

It was expected that both test and purchased garments L would be more difficult to doff than the garments S, and in some respects this was indeed the case. The time-to-doff appeared to be longer overall for Test Garment L than for Test Garment S. A study could be designed to determine whether this relationship holds true for several styles of garments which are doffed over the head. It appeared that the longer length of garment style L could hamper doffing, particularly if the gathered folds were released before the garment was removed from the head. During a pilot trial, this situation actually happened, and the shoulders and arms seemed to be crawling backwards out of the garment, while the right hand had to drag the garment forward, consuming extra time and energy. Another example is that the longer sleeves of garment L took time and effort to shed, while garment S, having no sleeves, required less. Graphs of each type of joint for each garment style were examined with these observed differences in the doffing movements in mind. Tables G1-4 in Appendix G provide the WATSMART data upon which the graphs are based.

Left Shoulder Angle

Figures 29a and b show typical graphs of the left shoulder angles obtained for the two test garments. In general, it appeared that the period prior to the rapid increase in

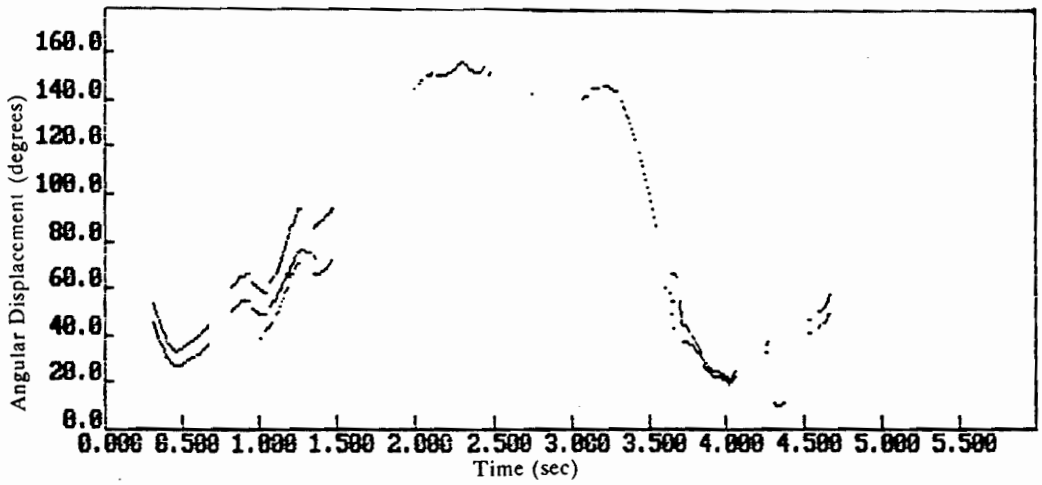


Figure 29a
Left Shoulder Angles, Test Garment S

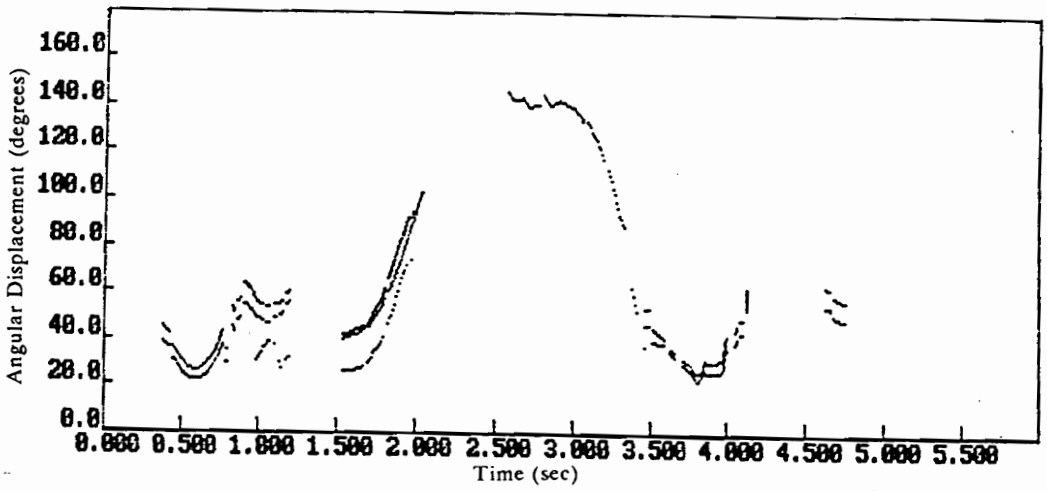


Figure 29b
Left Shoulder Angles, Test Garment L

shoulder angle was greater for the long test garments than the short. Since it is in this period that the garment is gathered to shorten its length, it is possible that the increase in time can be attributed to an attempt to secure more folds of Garment L. The angular displacement of the left shoulder was, however, very similar between both styles.

Right Shoulder Angle

Figures 30a and b show typical graphs of the right shoulder angles obtained for the two test garments. The variation of the angular displacement over time may be explained by the same reasons the left shoulder angle varied: the extra time needed to gather the longer garment. For posture (vii) the right shoulder angle appears to be greater in Test Garment S than for Test Garment L. This may be explained by the shorter armscye depth and more restrictive bodice construction of style L.

Left Elbow Angle

Figures 31a and b show typical graphs of the left elbow angles obtained for the two test garments. As the trials progressed, the later half of the movement became somewhat erratic, particularly for trials R011-R020 of Test Garment L (Appendix E). This is probably indicative of the extra effort needed to remove the long sleeve of that style. As described previously, this motion was basically a raking type motion, sometimes requiring several attempts before the sleeve was fully shedded. The amount of raking needed depended on the amount of garment still left on the right arm, which could vary from trial to trial. The angular displacements for posture (ii) resulting from doffing Test Garment L appear to be larger than those obtained from doffing Test Garment S. This indicates that the arm was more straight when the hands pinched the garment. This is probably due to the longer length of style L, which required more shortening to facilitate doffing.

Right Elbow Angle

Figures 32a and b show typical graphs of the right elbow angles obtained for the two test garments. The variation in the graphs as trials progressed can be attributed to the

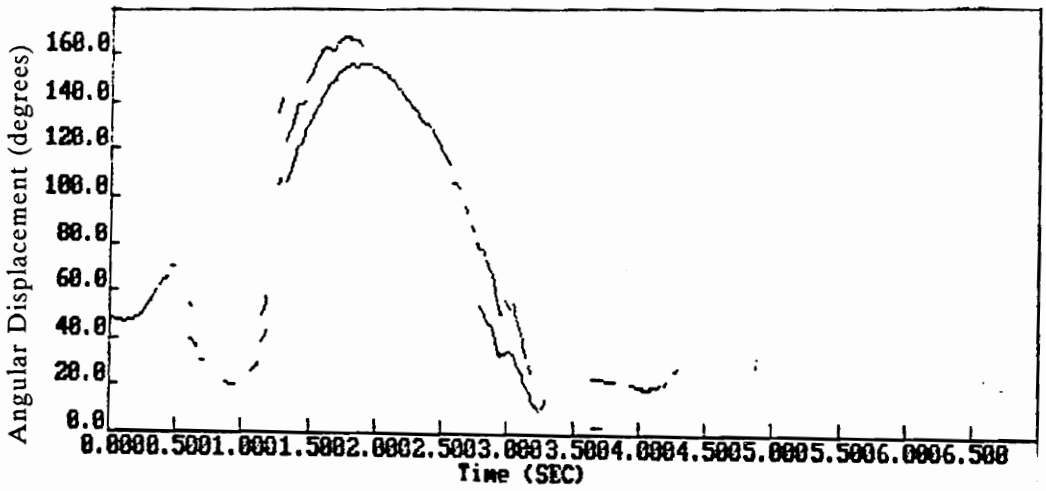


Figure 30b
Right Shoulder Angles, Test Garment S

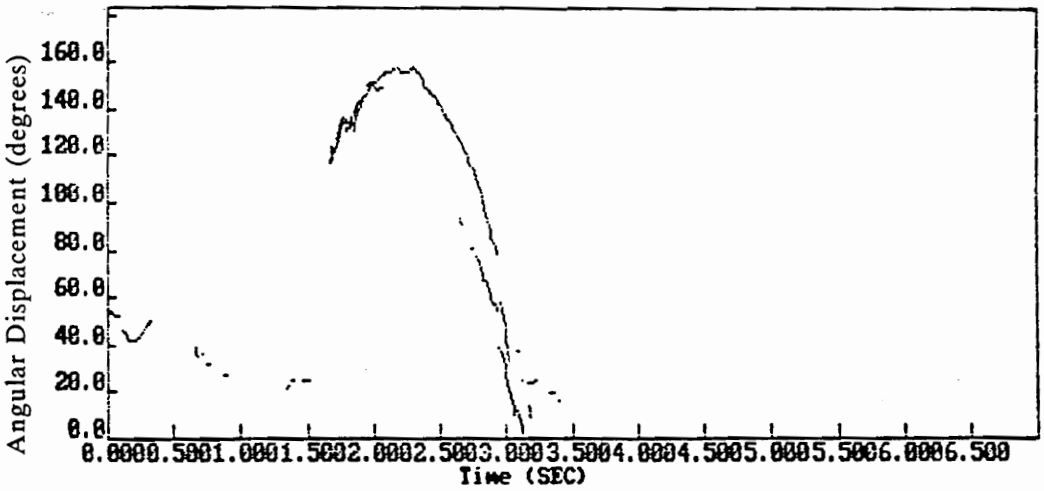


Figure 30a
Right Shoulder Angles, Test Garment L

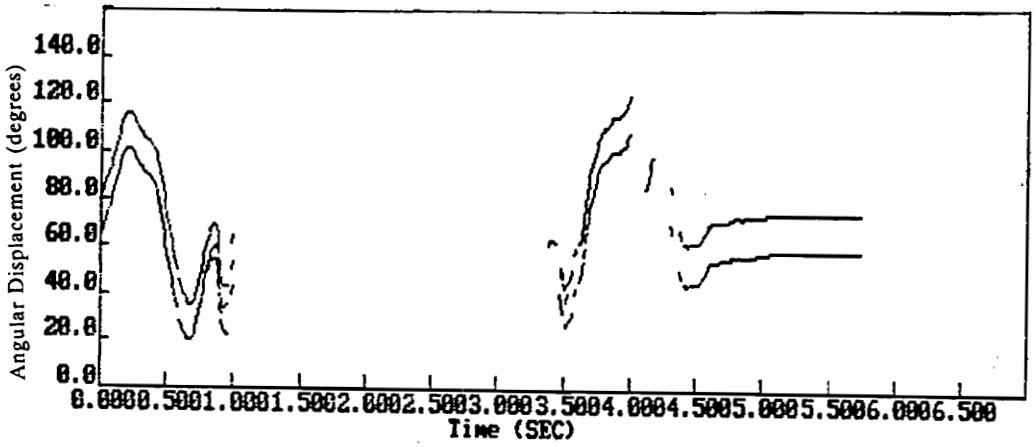


Figure 31a
Left Elbow Angles, Garment S

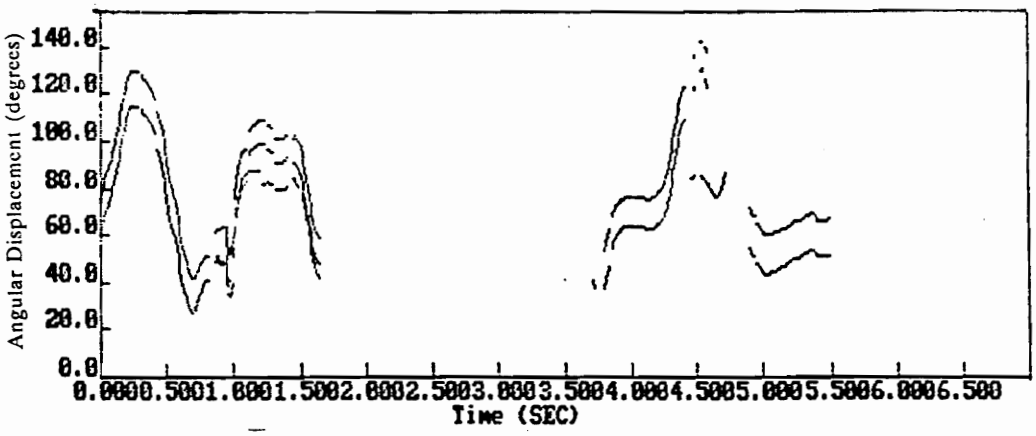


Figure 31b
Left Elbow Angles, Test Garment L

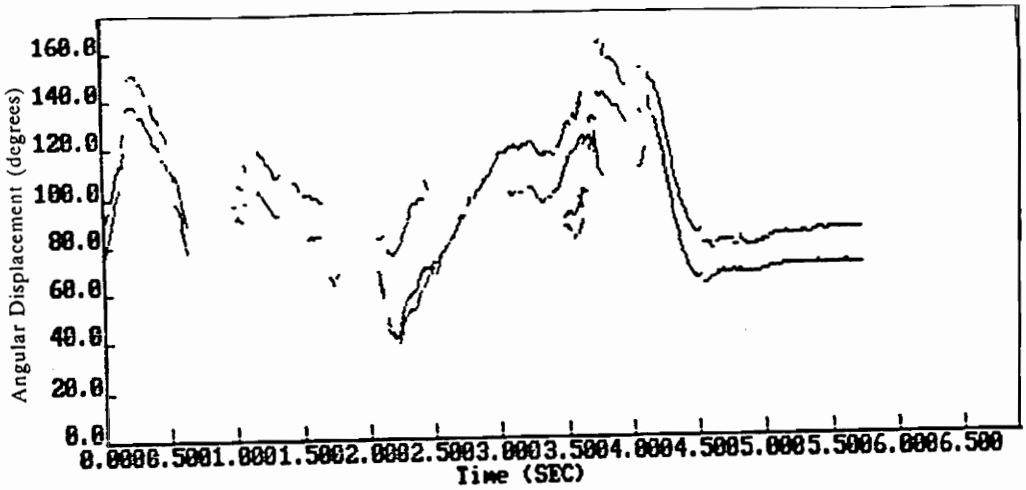


Figure 32a
Right Elbow Angles, Test Garment L

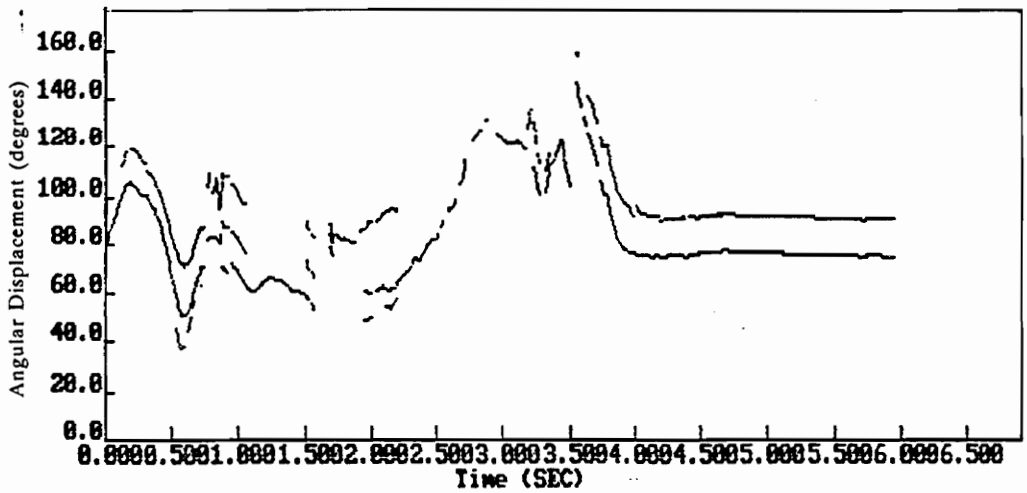


Figure 32b
Right Elbow Angles, Test Garment S

final removal of the right sleeve of Test Garment L. In trials R011-R020, it appeared to take more time to remove the garment from the lower torso, and to shed the right arm. The right elbow angle appeared to be greater overall during posture (vii) for Test Garments S, indicating that more extension was possible. This may be due to the absence of a sleeve on style S.

V-4.4. Summary of the Reliability of WATSMART Data

It appears that some variation exists in the WATSMART data due to different configurations of IREDs, differences in the garment styles, and to subject fatigue. Considering the variation sources and magnitude, it appears that the WATSMART data appear to consistently reflect the doffing movement occurring in each trial. The fact that the graphs are different from configuration to configuration of IREDs and from garment style S to L shows that WATSMART is sensitive enough to perceive the differences reliably.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

I. CONCLUSIONS

The purpose of this research was to develop and test a method for kinematic analysis of the doffing process for a specific garment. The specific objectives were to 1) identify the basic critical movements involved in the doffing process of a selected garment style, 2) quantify the movement pattern and 3) assess the validity of the method and reliability of the data.

The first objective, identifying the basic critical movements of the doffing process, was addressed by visually analyzing video films of doffings of both the test and purchased garments. Twelve movements were identified as representing the critical sequential movements of doffing and were separated into four phases of doffing: removal of the garment from the lower torso, removal of the garment from the upper torso, removal of the garment from the head, left shoulder, and arm; and removal of the garment from the right arm and shoulder. These 12 movements were also classified according to Roebuck's terminology.

The second objective, quantifying the movement pattern, involved in doffing, was accomplished by measuring the angular displacement of the various joints using a modification of the WATSMART system in which purchased garments made of opaque fabric simulated by test garments made of sheer fabric were worn over IREDs attached to the body. Different values for angular displacement were obtained for each joint since each joint could be defined by more than one configuration of IREDs. The movement experienced by the shoulder and elbow joints were close to the maximum physiologically possible. The time to doff appeared to be affected by the garment style, longer times being associated with Test Garment L.

The third objective, assessing the validity of the method and reliability of the data, was explored by determining the degree of agreement between the various components of the method. The degree of fidelity between the purchased garments and the test garments was assessed by a subjective judgment of the investigator based on the appearance of the movements, their sequence, and direction. Based on analysis of video films in terms of the direction of movement, the sequence and type of movements, the time of occurrence of the temporal matching postures and the fabric properties of the test and purchased garments, the degree of fidelity is not as assured as the degree of simulation, but no definitive statement can be made without further evaluation.

The construct validity of the method was assessed by matching position/time data obtained using the Posture Taxonomy instrument with those obtained by the WATSMART. The partial convergence of the position/time data from the two methods indicated that the WATSMART data agreed moderately with those obtained through video analysis. The reliability of the data was assessed in terms of intra-trial and inter-trial consistency Intra-trial inconsistencies were explained by the different configurations of IREDs possible to define each joint. Inter-trial inconsistencies were explained by the natural variation in human performance, fatigue, and differences in garment style.

Based on the general convergence of PT estimates and WATSMART calculations of angular displacement, and the satisfactory consistency of the data, it can be concluded that the method using the WATSMART system in this research to obtain range of motion data in doffing situations is feasible. Establishing the degree of fidelity of the garments would need to be more completely accomplished before the method can be used with confidence, however.

II. RECOMMENDATIONS FOR FURTHER RESEARCH

While generalizations cannot be made on the basis of the particular doffing data generated in this research, some observations were made which might further the

understanding of doffing activities and serve as a springboard for future research activities.

II-1. IMPROVING THE CONSISTENCY OF WATSMART DATA

One of the findings of this research was that there is an inherent error in the assumption that the same angular value would be obtained for a joint regardless of where IREDs were placed on that joint. As was shown, different angular values were obtained for the same joint for the same trial, i.e. intra-trial consistency was variable. Using triangulation techniques, it is possible to calculate a single center point from the markers assigned to a given joint. Theoretically, this point Could represent the "true" joint center, thus the best approximation of the angular displacement could be obtained.

II-2. RANGE OF MOTION REQUIREMENTS FOR THE DOFFING PROCESS

It appears that many extreme motions are required to perform an overhead doffing movement. In this study, the subject reached 97% of the maximum of the range of motion for at least the shoulder, according to Table 1 in the "Review of Literature". Were a person of limited mobility, e.g., an elderly person with arthritis, to attempt doffing these garments, they would likely have more difficulty accomplishing the movements, (if they could accomplish them at all) and would probably take more energy and time. This might be hazardous in situations where the garment needs to be doffed quickly under panic. The range of motion and time to doff of people with varying mobility could be studied to determine the optimal dimensions and style of a garment that would require the least energy and time to doff.

II-3. FURTHER VALIDATION OF THE METHOD

While the WATSMART data obtained were found to be satisfactory, other three-dimensional systems may also be useful for obtaining accurate range of motion data. It would be illuminating to compare range of motion data of the doffing process obtained by other electro-optical (or even non-optical) systems to that obtained by WATSMART. WATSMART, because it is so sensitive to infrared reflection and because it uses averages

to define the location of IREDs, may not be as accurate as some other types of systems. Also, the active-type markers used in this research may have interfered with the normal doffing process, the extent of which should be determined before the using the method to generate definitive doffing data.

In exploring the validation of another system, it would probably be sufficient in the future for the subject to practice doffing the garment five times before then doffing for recording range of motion data. The point of constant skill level was determined by movement pattern represented by the position vs. time data obtained by WATSMART and the appearance of the movement: when the skill level was constant, the position vs. time graphs followed similar patterns, and the movements in the films looked alike, including performance in the same sequence. Consistent skill level appears to have been maintained throughout the doffing trials after R003, but the doffings appeared to be slower as the trials neared 20 because the subject grew fatigued. It can be assumed that any doffings after R005 represented the "true" doffing movement as the subject was well-practiced at that point. If video filming is again selected as a means for validation, it would probably be helpful to film the overhead view to provide a more complete record of the doffing process.

II-4. DETERMINATION OF BASIC DOFFING MOVEMENTS OF THE GENERAL POPULATION

Determining the representative doffing movements of the general population would be a first step in designing garments on a large scale to be doffed more easily. In particular, this information could be coupled with range of motion data to determine the optimal dimensions and configuration of garments for those of limited mobility and coordination, such as children and the elderly. Use of a system, like the WATSMART, would make data acquisition of a population much easier, less time-consuming, and very thorough. The same information could be garnered by the video analysis techniques

employed in the current research, but the collection time of 75 hours to gather video data on the doffing process is obviously the less desirable alternative.

II-5. DEVELOPMENT OF A SYSTEM FOR EVALUATION OF DYNAMIC CLOTHING TASKS

Developing a method to validate the WATSMART three- dimensional data of a dynamic movement (doffing) was difficult because most systems are designed for static, not dynamic, analyses. Another difficulty is that no systems have been developed specifically to analyze clothing tasks. The Posture Taxonomy instrument, as was pointed out, is ideally suited for analysis of static postures, not dynamic movements. Dance notation systems, while designed for recording dynamic movements, have been found to be too difficult to learn to be practical. Apart from these lacks, a system of terminology describing manipulation of fabric is needed to standardize analyses of clothing tasks. For instance, a garment can be manipulated upward by pulling up on the hem of the garment or gathering the garment. In the former case, the garment turns inside out, while in the latter the garment's face side remains oriented outermost. The differences result in change in the orientation of the garment from the frontal plane to the transverse plane. As is evidenced by the verbose and unclear description just offered, use of a standardized clothing vocabulary would add clarity and depth to the ability to describe and analyze clothing behavior, in much the same way the specialized vocabulary developed for human movement made motion analyses meaningful.

II-6. EXPLORING THE GARMENT DYNAMICS OF DOFFING

The behavior of the test and purchased garments while being doffed shared certain characteristics. It appears that the tension imposed by the garment influences the removal of a garment. It appears that tension impedes doffing as evidenced by the efforts of the body to reconfigure itself to be as small as possible, increasing what Kakitsuba, Michna, and Mekjavic (1987) call the clothing microenvironment volume, the space between the body and the interior "wall" of the garment.

It appeared from the video films that during the head-left arm removal phase, tension was applied by the head. To help the right arm pull off a garment, the left shoulder, arm, and forearm moved as a bent unit toward the head which was bent, apparently to reduce tension on the garment and release it to move as the right arm directed. Not only doffing movements, but also donning movements could be studied for the relationship between the tension applied and released by body volume to enable fabric movement.

II-7. MOTOR LEARNING ACQUIRED DURING THE DOFFING PROCESS

As the video films were viewed, it was observed that as the trials progressed some movements were eliminated, while others changed slightly to become smoother, faster. For example, in the earlier trials, the subject pushed the garment off the right arm, while in later trials the subject pulled the garments off, resulting in a faster discard of the garment. Another example of this occurred when the garment had been removed from the head and left shoulder, and was being taken from above head level down to the waist level. This movement occurred in the frontal plane at first but later occurred in the sagittal plane. While the movement of the right arm culminated in the same spot no matter the path, it appeared that moving in the sagittal plane allowed a symmetry of movement with the left arm. It can be speculated as to whether these changes facilitated the movement in some way, from the interaction of shoulder and back antagonist/agonist pairs, or some other mechanism, but the subject in both instances made apparently subconscious decisions to improve the efficiency of the motion. The process of learning to accomplish clothing tasks, and then to optimize the efficiency could be studied, and the knowledge applied to the design of clothing articles for young children. The effect of "righthandedness" or "lefthandedness" on the performance of doffing is another aspect of motor learning that might be useful to study.

II-8. APPLICATION OF DOFFING DATA TO SAFETY ISSUES

Doffing data could be useful in developing a hazard index, as advocated by Solinger (1980), to assess the flammability hazard of garments, where the ease of doffing is based on the range of motion as a determinant of the index. It has long been acknowledged that a computerized robot mimicking the motions of a human being in a hazardous situation would be a very useful way to assess the hazard of garments. Unfortunately, such a robot does not yet exist, but if and when it is developed, the sequence of movements could be programmed into a robot so that it would doff the garment as it is burned, corroded by chemicals, etc. The advantage of such a burning is that it would have a high degree of simulation and fidelity to real life clothing fires which current flammability test methods employing immobile mannequins do not. This programmed sequence of movements would be useful in any simulation where doffing is an important factor in safety.

Doffing data could also be used to derive the necessary dimensional requirements of garments to accomplish the doffing process. Previous research has concentrated on fastening systems to aid doffing, and on small-scale volumetric alterations to expand garment areas where needed (Atkin, 1980; Hoffman, 1978; Hogge & Baer, 1986; Kirk & Ibrahim, 1966; Reich, 1986; Watkins, 1984). It appears that no attempts have been made to use motion data to derive garment dimensions for doffing. The data could be integrated with studies on body expansion, the artificial dimension given to the human form by a garment (King, 1979). Body expansion has been found to increase the hazard of garments, as illustrated by the ignition of long flowing sleeves drooping over a stove burner. While too much garment volume can be hazardous because of risk of ignition, entanglement in machinery and the like, too little garment volume can be hazardous because of an inability to doff the garment quickly in dangerous situations.

CHAPTER SEVEN

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APPENDICES

APPENDIX A

TRADITIONAL TERMINOLOGY

Term	Meaning
Flexion	bending a joint so that the two adjacent segments approach each other and joint angle decreases
Extension	straightening the joint so the two adjacent segments move away from each other and joint angle increases
Supination	rotating the forearm so that the palm is up (anterior in the anatomical position)
Pronation	rotating the forearm so that the palm is is down (posterior in the anatomical position)
Abduction	motion at a joint so that a segment is moved laterally away from middle of body
Adduction	motion at a joint so that a segment is moved medially toward the middle of body
Rotation	turning or moving of a part around its axis

APPENDIX B

INSTRUCTIONS FOR THE USE OF THE POSTURE TAXONOMY RECORDING FORMS

(Reprinted with permission from Posture Taxonomy by Robert Malone, 1991)

The three forms correspond to the front, top, and side views of the person whose posture is being recorded. The basis of the recording method is a representative model of the human body which breaks the body down into its major limbs and sections. As may be seen from the forms, the limbs and sections of interest are: the thighs, calves, forearms, upper arms, the trunk, and the hips.

Targets are provided on each form corresponding to the limbs. It should be apparent which target represents which limb. The targets consist of different representations of the limb corresponding to the different angles the limbs may adopt as they move through their range of motion.

Recording the posture of the body is done by recording the position (angle) of each limb. To record the position of a limb, one simply has to choose the limb in the target that is closest to the actual angle of the limb in space, and record the appropriate target limb by making a mark in the recording box adjacent to it.

Only one target is provided for each of the left and right limbs. The recording box is marked l and r by column to keep the recording of the limbs separated. The l and r designations refer to the person whose posture is being recorded and not the frame of reference of the recorder. The model is capable of tabulating frequency data; five different postures may be recorded on one diagram. To identify separate posture recordings, the recording scales for each limb are marked 1 to 5 from innermost to outermost row.

Many different postures may be assumed by the human in the side view. It is necessary to orient the sagittal plane recording diagram to suit which general type of posture is being recorded. The sagittal plane diagram is annotated at the margins as to which orientation should be adopted for the various possible postures.

There are a few points about this recording method that should be noted. First, the position of the thighs is not recorded in the front view when the person is sitting down. The position of the thighs is not recorded in the top view when the person is standing up. In the top view, all the angles are taken with reference to the angle of the limb.

APPENDIX C

GLOSSARY OF ROEBUCK'S TERMINOLOGY
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Terms Denoting Types of Movement

1.	Principal Director	The vector assigned to each body segment.
2.	Rotary Director	An axial rotation vector assigned to each body segment.
3.	Vection	Pivoting or revolving the principal director or its projection on a principal plane, about an axis perpendicular to itself.
4.	Rotation	A rotary movement of a link about its major axis, or principal director. Described as an angular direction change (vection) of the rotary director.
5.	Torsion	Twisting of a link about its major axis, described as an angular direction change (vection) of the rotary director assuming the tail of the principal director is fixed.

Terms Denoting Direction of Movement - Single Links

1.	Posivection	Vection in any plane producing an increasing angular reading in that plane. The plane in which action is measured must be specified by a preceding term, i.e., frontal, sagittal, transversal.
2.	Negivection	Opposite of posivection.
3.	Positive rotation	As seen from the tail of the principal director, rotation resulting in clockwise vection of the rotary director.
4.	Negative Rotation	Opposite to positive rotation
5.	Positive Torsion	As seen from the tail of the Principal Director, rotation resulting in clockwise vection of the rotary director.
6.	Negative Torsion	Opposite to positive torsion.

Terms Denoting Direction of Movement - Dual Links

The major terms for dual links are formed by combining the three terms denoting

type of movement with the following prefix elements indicating direction:

(1)	-e-	A positive upward or outward tending movement (from the standard position), or any motion resulting in an increasing angular coordinate of the right limb.
(2)	-in-	Opposite to -e-, an inward or downward movement.
(3)	Front-	The first syllable of each of the
(4)	Sag-	of the names for the principal planes.
(5)	Trans-	

1.	Frontevection	As seen from the front, clockwise vection of the right limb together with counterclockwise vection of the left limb about axes perpendicular to the frontal plane.
2.	Frontinvection	Opposite to frontevection.
3.	Sagevection	As seen from the right, counterclockwise vection of the limbs about an axis perpendicular to the sagittal plane.
4.	Saginvection	Opposite to frontevection.
5.	Transevection	As seen from above, clockwise vection of the right limb together with counterclockwise vection of the left limb about axes perpendicular to the transverse plane.
6.	Transinvection	Opposite to transevection.
7.	Fronterotation	Frontevection of the rotary directors of the limbs. **Positive fronterotation** implies that the principal director is pointing in the positive X direction , or forward. **Negative fronterotation** implies that the principal director is pointing aft, or in the minus X direction.
8.	Frontinrotation	Opposite to fronterotation. Frontinvection of the rotary directors of the limbs. As in above, **positive** implies that the principal director points forward; **negative** implies that the principal director points aft.
9.	Sagerotation	Sagevection of the rotary directors of dual links. **Positive** implies that the principal director of the right limb is pointing to the right, or in the positive Y direction, and opposite for the left limb. **Negative** implies that the right limb is pointing left and the left limb is pointing right.

10.	Saginrotation	Saginvection of the rotary director of dual links. The terms **positive** and **negative** apply as in sagerotation above.
11.	Transerotation	Transevection of the rotary directors of the limbs. **Positive** implies that the principal director of the links points downward, in the direction of the Z axis; **negative** implies the opposite.
12.	Transinrotation	Transinvection of the rotary directors of the limbs. The terms **positive** and **negative** apply as in transerotation above.
13.	Frontetorsion	Frontevection of the rotary directors of the limbs, with the tail end of the principal directors held fixed. The terms **positive** and **negative** apply as for fronterotation.
14.	Frontintorsion	Opposite of fronterotation.
15.	Sagetorsion	Sagevection of the rotary directors of the limbs with the tail end of the principal directors held fixed. The terms **positive** and **negative** apply as for sagerotation.
16.	Sagintorsion	Opposite of sagetorsion.
17.	Transetorsion	Transevection of the rotary directors of the limbs with the tail end of the principal directors held fixed. The terms **positive** and **negative** apply as for transerotation.
18.	Transintorsion	Opposite to transetorsion.

APPENDIX D
FRAME COUNTS OF THE TIME OF OCCURRENCE OF TEMPORAL MATCHING POSTURES

Table D-1a
Temporal Matching Posture (i)
Time of Occurrence in Frames and Seconds

(no data are displayed since the
starting time is 0.00 seconds for all trials)

Table D-1b
Temporal Matching Posture (ii)
Time of Occurrence in Frames and Seconds

Test Garment S								
Trial	Frame Ct. 1	Time Ct. 1	Frame Ct. 2	Time Ct. 2	Frame Ct. 3	Time Ct. 3	Mean	S.D.
R001	24	.40	22	.37	20	.33	.367	.35
R002	21	.35	17	.28	18	.30	.310	.36
R003	18	.30	16	.27	16	.27	.280	.017
R004	21	.35	18	.30	18	.30	.317	.029
R005	17	.28	n/d	n/d	16	.27	.275	.007
R006	17	.28	17	.28	24	.40	.320	.069
R007	25	.42	22	.37	18	.30	.363	.060
R008	22	.37	18	.30	15	.25	.307	.060
R009	23	.38	17	.28	21	.35	.337	.051
R010	26	.43	n/d	.37	22	.37	.400	.042
Test Garment L								
R011	24	.40	22	.37	24	.40	.390	.017
R012	29	.48	26	.43	28	.47	.460	.026
R013	25	.42	24	.40	25	.42	.413	.011
R014	27	.45	24	.40	28	.47	.440	.036
R015	21	.35	n/d	n/d	21	.35	.350	.000
R016	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R017	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R018	21	.35	22	.37	25	.42	.395	.035
R019	22	.37	22	.37	20	.33	.320	.036
R020	26	.43	17	.28	17	.28	.325	.064

Table D-1c
Temporal Matching Posture (iv), Right Side
Time of Occurrence in Frames and Seconds

Test Garment S								
Trial	Frame Ct. 1	Time Ct. 1	Frame Ct. 2	Time Ct. 2	Frame Ct. 3	Time Ct. 3	Mean	S.D.
R001	85	1.42	92	1.53	90	1.52	1.49	.061
R002	78	1.30	85	1.42	83	1.38	1.37	.061
R003	80	1.33	84	1.40	86	1.43	1.39	.051
R004	71	1.18	76	1.27	74	1.23	1.23	.045
R005	86	1.43	75	1.25	82	1.37	1.35	.092
R006	86	1.43	86	1.43	85	1.42	1.43	.006
R007	82	1.37	90	1.50	93	1.55	1.47	.093
R008	99	1.65	85	1.42	83	1.38	1.48	.146
R009	90	1.50	100	1.67	101	1.68	1.62	.100
R010	101	1.68	95	1.58	95	1.58	1.61	.060
Test Garment L								
R011	112	1.87	108	1.80	107	4.78	1.82	.047
R012	99	1.65	112	1.87	110	1.83	1.78	.117
R013	98	1.63	92	1.53	95	1.58	1.58	.05
R014	85	1.42	99	1.65	94	1.57	1.55	.117
R015	98	1.63	90	1.50	85	1.42	1.52	.106
R016	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R017	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R018	88	1.47	108	1.80	104	1.73	1.67	.174
R019	82	1.37	97	1.62	95	1.58	1.52	.134
R020	85	1.42	85	1.42	83	1.38	1.41	.023

Table D-1c (cont'd)
Temporal Matching Posture (iv), Left Side
Time of Occurrence in Frames and Seconds

Test Garment S								
Trial	Frame Ct. 1	Time Ct. 1	Frame Ct. 2	Time Ct. 2	Frame Ct. 3	Time Ct. 3	Mean	S.D.
R001	101	1.68	86	1.43	87	1.45	1.52	.139
R002	86	1.43	91	1.52	95	1.58	1.51	.075
R003	91	1.52	89	1.48	79	1.32	1.44	.106
R004	81	1.35	90	1.52	91	1.52	1.46	.098
R005	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R006	92	1.53	91	1.52	93	1.55	1.53	.015
R007	100	1.67	94	1.57	105	1.75	1.66	.090
R008	92	1.53	95	1.58	85	1.42	1.51	.082
R009	109	1.82	112	1.87	101	1.68	1.79	.098
R010	110	1.83	105	1.75	99	1.65	1.74	.090
Test Garment L								
R011	120	2.00	112	1.87	99	1.65	1.84	.177
R012	95	1.58	100	1.67	111	1.85	1.70	.137
R013	100	1.67	96	1.60	100	1.67	1.63	.030
R014	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R015	100	1.67	100	1.58	98	1.63	1.63	.069
R016	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R017	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R018	114	1.9	100	1.67	112	1.87	1.81	.125
R019	100	1.67	84	1.35	109	1.82	1.69	.297
R020	100	1.67	114	1.90	96	1.60	1.70	.213

Table D-1d
Temporal Matching Posture (vii)
Time of Occurrence in Frames and Seconds

Test Garment S								
Trial	Frame Ct. 1	Time Ct. 1	Frame Ct. 2	Time Ct. 2	Frame Ct. 3	Time Ct. 3	Mean	S.D.
R001	140	2.33	143	2.38	114	1.90	2.20	.264
R002	114	1.90	114	1.90	115	1.92	1.91	.012
R003	113	1.18	115	1.92	110	1.83	1.88	.045
R004	116	1.93	121	2.02	106	1.77	1.91	.127
R005	99	1.65	117	1.95	100	1.67	1.76	.168
R006	118	1.97	130	2.17	100	1.67	1.94	.252
R007	130	2.17	119	1.98	121	2.02	2.06	.100
R008	135	2.25	115	1.92	111	1.85	2.01	.214
R009	145	2.42	146	2.43	127	2.12	2.32	1.76
R010	133	2.22	140	2.23	121	2.02	2.07	.185
Test Garment L								
R011	137	2.28	115	1.92	132	2.20	1.96	.585
R012	148	2.47	125	2.08	138	2.30	1.96	.585
R013	136	2.27	137	2.28	127	2.12	2.06	.255
R014	137	2.28	107	1.78	107	1.78	1.89	.093
R015	117	1.95	116	1.93	101	1.68	1.84	.139
R016	115	1.92	115	1.92	119	1.98	2.09	.252
R017	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
R018	143	2.38	115	1.92	118	1.97	2.17	.168
R019	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
R020	138	2.30	125	2.08	126	2.10	2.16	.122

Table D-1e
Temporal Matching Posture (viii), Left Side
Time of Occurrence in Frames and Seconds

Test Garment S								
Trial	Frame Ct. 1	Time Ct. 1	Frame Ct. 2	Time Ct. 2	Frame Ct. 3	Time Ct. 3	Mean	S.D.
R001	152	2.53	160	2.67	161	2.68	2.63	.084
R002	135	2.25	134	2.23	134	2.23	2.24	.012
R003	150	2.50	135	2.25	142	2.37	2.37	.125
R004	136	2.27	145	2.42	139	2.32	2.34	.076
R005	148	2.47	144	2.40	146	2.43	2.43	.035
R006	136	2.27	149	2.48	147	2.45	2.40	.114
R007	160	2.67	159	2.65	163	2.72	2.68	.036
R008	164	2.73	154	2.57	150	2.50	2.60	.118
R009	164	2.73	162	2.70	160	2.67	2.70	.036
R010	146	2.43	170	2.83	170	2.83	2.69	.231
Test Garment L								
R011	166	2.76	165	2.75	165	2.75	2.75	.006
R012	176	2.93	171	2.85	166	2.77	2.85	.080
R013	158	2.63	150	2.50	149	2.48	2.54	.080
R014	153	2.55	156	2.60	160	2.67	2.61	.060
R015	130	2.17	140	2.33	141	2.35	2.28	.099
R016	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R017	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R018	160	2.67	173	2.88	171	2.85	2.80	.114
R019	156	2.60	157	2.62	150	2.50	2.57	.064
R020	157	2.62	160	2.67	159	2.65	2.65	.025

Table D-1e (cont'd)
Temporal Matching Posture (viii), Right Side
Time of Occurrence in Frames and Seconds

Test Garment S								
Trial	Frame Ct. 1	Time Ct. 1	Frame Ct. 2	Time Ct. 2	Frame Ct. 3	Time Ct. 3	Mean	S.D.
R001	196	3.27	143	2.38	144	2.40	2.68	.508
R002	143	2.38	146	2.43	156	2.60	2.47	.115
R003	160	2.67	140	2.33	126	2.10	2.37	.287
R004	130	2.17	135	2.25	140	2.33	2.21	.057
R005	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R006	139	2.32	148	2.47	148	2.47	2.42	.087
R007	148	2.47	146	2.43	168	2.80	2.57	.203
R008	146	2.43	151	2.52	152	2.53	2.49	.055
R009	155	2.58	170	2.83	167	2.78	2.73	.132
R010	147	2.45	166	2.77	167	2.78	2.67	.187
Test Garment L								
R011	165	2.75	149	2.48	147	2.45	2.56	.165
R012	149	2.48	145	2.42	155	2.58	2.49	.081
R013	146	2.43	150	2.50	160	2.67	2.53	.121
R014	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R015	164	2.73	153	2.55	147	2.45	2.58	.142
R016	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R017	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R018	162	2.70	160	2.67	159	2.65	2.67	.025
R019	140	2.33	128	2.13	159	2.65	2.37	.267
R020	142	2.37	161	2.68	145	2.42	2.49	.166

Table D-1f
Temporal Matching Posture (xii)
Time of Occurrence in Frames and Seconds

Test Garment S								
Trial	Frame Ct. 1	Time Ct. 1	Frame Ct. 2	Time Ct. 2	Frame Ct. 3	Time Ct. 3	Mean	S.D.
R001	285	4.75	290	4.83	280	4.67	4.75	.08
R002	256	4.27	250	4.17	253	4.22	4.22	.05
R003	258	4.30	297	4.95	284	4.73	4.66	.33
R004	278	4.63	286	4.76	260	4.33	4.57	.22
R005	258	4.30	n/d	n/d	267	4.45	4.38	.11
R006	247	4.12	273	4.55	248	4.13	4.27	.245
R007	248	4.13	255	4.25	280	4.67	4.35	.283
R008	284	4.73	275	4.58	285	4.75	4.69	.092
R009	277	4.62	285	4.75	282	4.70	4.69	.066
R010	264	4.40	264	4.40	250	4.17	4.29	.163
Test Garment L								
R011	300	5.00	302	5.03	300	5.00	5.01	.017
R012	295	4.92	293	4.88	296	4.93	4.91	.026
R013	282	4.70	280	4.67	287	4.78	4.72	.057
R014	284	4.73	286	4.76	285	4.75	4.75	.013
R015	247	4.12	n/d	n/d	252	4.20	4.16	.057
R016	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R017	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R018	n/d	n/d	282	4.70	290	4.83	4.77	.092
R019	278	4.63	263	4.38	271	4.57	4.53	.131
R020	280	4.22	n/d	n/d	278	4.63	4.43	.290

APPENDIX E
COMPARISON OF WATSMART AND POSTURE TAXONOMY VALUES FOR ANGULAR DISPLACEMENT

Table E-1a
Comparison of PT and WATSMART Data for Temporal Matching Posture (i), Test Garment S

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R001	0.00	n/d	59	n/d	51	0.00	n/d	96	n/d	44
R002	0.00	105	63	45	45	0.00	110	115	45	54
R003	0.00	110	70	45	48	0.00	120	95	30	48
R004	0.00	105	69	45	52	0.00	105	123	30	51
R005	0.00	105	69	30	54	0.00	110	123	45	44
R006	0.00	110	69	45	57	0.00	105	113	45	55
R007	0.00	110	66	30	51	0.00	105	115	45	42
R008	0.00	110	71	45	49	0.00	110	98	45	44
R009	0.00	105	66	45	53	0.00	110	91	45	55
R010	0.00	110	67	45	54	0.00	110	107	45	54
Mean	0.00	107.5	66.9	42	51.4	0.00	109.4	107.6	41.7	44.1

Table E-1b
Comparison of PT and WATSMART Data for Temporal Matching Posture (ii)
Test Garment S

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R001	.367	120	83	30	51	.367	120	n/d	30	n/d
R002	.310	n/d	90	30	34	.310	n/d	117	15	34
R003	.280	105	98	30	n/d	.280	120	91	30	53
R004	.317	110	68	30	31	.317	110	118	45	39
R005	.275	120	88	30	38	.275	150	111	15	43
R006	.320	120	107	30	33	.320	120	110	45	35
R007	.363	135	92	30	n/d	.363	120	100	30	49
R008	.307	105	98	30	45	.307	120	100	30	46
R009	.337	135	92	15	35	.337	150	104	12	45
R010	.400	120	97	30	39	.400	120	95	30	46
Mean	.328	118.9	91.3	28.3	38.3	.328	125.6	155.3	28.5	43.3

Table E-1c
Comparison of PT and WATSMART Data for Temporal Matching Posture (vi)
Test Garment S

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R001	1.49	n/d	n/d	90	n/d	1.52	n/d	57	90	127
R002	1.37	n/d	n/d	90	97	1.51	n/d	92	90	54
R003	1.39	n/d	n/d	90	n/d	1.44	n/d	81	90	119
R004	1.23	n/d	n/d	90	92	1.46	n/d	89	90	52
R005	1.35	n/d	n/d	90	n/d	n/d	n/d	n/d	90	n/d
R006	1.43	n/d	n/d	90	84	1.53	n/d	n/d	90	n/d
R007	1.47	n/d	n/d	90	n/d	1.66	n/d	75	90	106
R008	1.48	n/d	n/d	90	76	1.51	n/d	n/d	90	n/d
R009	1.62	n/d	n/d	90	n/d	1.79	n/d	79	90	103
R010	1.61	n/d	n/d	90	n/d	n/d	n/d	76	90	105
Mean	1.44	n/d	n/d	90	87.3	1.55	n/d	78.4	90	95.1

Table E-1d
Comparison of PT and WATSMART Data for Temporal Matching Posture (vii)
Test Garment S

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R001	2.20	n/d	n/d	n/d	147	2.20	n/d	110	180	155
R002	1.91	90	n/d	180	142	1.98	90	67	180	152
R003	1.88	90	n/d	180	150	1.88	90	57	180	157
R004	1.91	90	n/d	180	154	1.91	90	59	180	157
R005	1.76	90	n/d	180	148	1.76	90	n/d	180	136
R006	1.97	105	n/d	180	148	1.94	90	61	180	141
R007	2.06	105	n/d	195	151	2.06	90	57	180	158
R008	2.01	105	n/d	180	149	2.01	90	63	180	143
R009	2.32	105	n/d	180	n/d	2.32	90	55	180	157
R010	2.28	120	n/d	195	n/d	2.88	90	68	180	155
Mean	2.26	98.3	n/d	183.5		2.09	90	66.3	180	150.9

Table E-1e
Comparison of PT and WATSMART Data for Temporal Matching Posture (viii)
Test Garment S

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R001	2.63	n/d	n/d	165	137	2.68	n/d	140	150	117
R002	2.24	n/d	n/d	180	146	2.68	n/d	93	150	155
R003	2.37	n/d	n/d	180	n/d	2.37	n/d	77	165	132
R004	2.34	n/d	n/d	165	n/d	2.21	n/d	76	165	144
R005	2.43	n/d	n/d	165	143	n/d	n/d	65	165	149
R006	2.40	n/d	n/d	165	143	2.42	n/d	77	165	152
R007	2.68	n/d	n/d	180	n/d	2.57	150	68	180	137
R008	2.60	n/d	n/d	165	150	2.49	n/d	84	150	148
R009	2.70	n/d	n/d	180	152	2.73	n/d	95	165	161
R010	2.69	n/d	n/d	150	148	2.51	n/d	106	180	140
Mean	2.51	n/d	n/d	170	145.6	2.49	n/d	88.1	159	143.9

Table E-1f
Comparison of PT and WATSMART Data for Temporal Matching Posture (xii)
Test Garment S

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R001	4.75	n/d	65	n/d	n/d	4.75	n/d	91	n/d	n/d
R002	4.22	105	65	45	49	4.22	110	118	45	n/d
R003	4.66	110	100	45	n/d	4.66	120	85	30	n/d
R004	4.57	105	51	45	n/d	4.57	105	90	30	n/d
R005	4.36	105	123	30	57	4.36	110	89	45	n/d
R006	4.27	110	50	45	n/d	4.27	105	91	45	n/d
R007	4.35	110	117	30	60	4.35	105	93	45	n/d
R008	4.69	110	62	45	n/d	4.69	110	92	45	n/d
R009	4.69	105	45	45	n/d	4.69	110	87	45	n/d
R010	4.29	110	73	45	n/d	4.29	110	83	45	n/d
Mean	4.49	107.5	75.1	42	55.3	4.49	109.4	91.9	41.7	n/d

Table E-2a
Comparison of PT and WATSMART Data for Temporal Matching Posture (i)
Test Garment L

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R011	0.00	110	57	45	61	0.00	110	85	45	54
R012	0.00	110	68	45	48	0.00	110	90	45	52
R013	0.00	110	67	45	44	0.00	110	n/d	45	n/d
R014	0.00	110	71	45	51	0.00	110	n/d	45	n/d
R015	0.00	110	62	45	47	0.00	110	n/d	45	n/d
R016	0.00	110	n/d	45	n/d	0.00	110	n/d	45	n/d
R017	0.00	110	n/d	n/d	n/d	0.00	n/d	n/d	n/d	n/d
R018	0.00	110	66	45	48	0.00	110	n/d	45	n/d
R019	0.00	110	71	45	46	0.00	110	n/d	45	55
R020	0.00	75	64	60	46	0.00	110	83	45	63
Mean	0.00	106.1	65.8	46.7	48.9	0.00	110	86.0	45	56

Table E-2b
Comparison of PT and WATSMART Data for Temporal Matching Posture (ii)
Test Garment L

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R011	.460	n/d	63	n/d	38	.460	n/d	101	n/d	51
R012	.413	150	123	15	23	.413	150	132	15	29
R013	.440	150	118	15	34	.440	150	n/d	15	n/d
R014	.350	150	125	15	26	.350	150	n/d	15	39
R015	.332	150	62	15	25	.332	150	n/d	15	n/d
R016	.332	150	n/d	15	n/d	.332	150	n/d	15	n/d
R017	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R018	.395	150	97	15	28	.395	150	107	15	47
R019	.320	n/d	74	n/d	31	.320	n/d	102	n/d	50
R020	.325	150	69	15	26	.325	150	117	15	42
Mean	.379	150	91.4	15	28.9	.379	150	111.8	15	43.0

Table E-2c
Comparison of PT and WATSMART Data for Temporal Matching Posture (vi)
Test Garment L

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R011	1.82	n/d	91	90	n/d	1.74	n/d	n/d	90	n/d
R012	1.78	n/d	n/d	90	92	1.84	n/d	93	90	53
R013	1.58	n/d	n/d	90	97	1.70	n/d	n/d	90	n/d
R014	1.55	n/d	n/d	90	93	1.63	n/d	n/d	90	n/d
R015	1.52	n/d	n/d	90	n/d	1.87	n/d	n/d	90	n/d
R016	1.60	n/d	n/d	90	n/d	n/d	n/d	n/d	90	n/d
R017	n/d	n/d	n/d	90	n/d	n/d	n/d	n/d	90	n/d
R018	1.67	n/d	n/d	90	90	1.81	n/d	n/d	90	n/d
R019	1.52	n/d	n/d	90	81	1.69	n/d	86	90	n/d
R020	1.41	n/d	n/d	90	n/d	1.70	n/d	82	90	43
Mean	1.61	n/d	n/d	90	90.6	1.75	n/d	60.3	90	n/d

Table E-2d
Comparison of PT and WATSMART Data for Temporal Matching Posture (vii)
Test Garment L

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R011	1.96	120	91	180	n/d	2.07	90	72	180	118
R012	2.28	90	n/d	165	n/d	2.28	90	56	180	138
R013	2.06	90	n/d	180	151	2.06	90	54	180	151
R014	1.89	120	n/d	180	146	1.89	90	67	180	128
R015	1.84	105	n/d	180	148	1.84	75	46	195	146
R016	2.09	120	n/d	195	n/d	2.09	90	n/d	180	n/d
R017	n/d6	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R018	2.17	105	n/d	180	n/d	2.17	105	55	180	138
R019	n/d	90	n/d	180	n/d	n/d	90	n/d	180	n/d
R020	2.16	105	n/d	180	n/d	2.16	90	46	180	139
Mean	2.06	105	n/d	180	148.3	2.07	90	56.6	181.7	135.4

Table E-2e
Comparison of PT and WATSMART Data for Temporal Matching Posture (viii)
Test Garment L

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R011	2.75	n/d	n/d	180	147	2.67	n/d	112	165	141
R012	2.85	n/d	n/d	165	146	2.56	n/d	102.3	150	137
R013	2.54	n/d	n/d	180	145	2.49	n/d	95	165	144
R014	2.61	n/d	n/d	180	153	2.53	n/d	107	165	150
R015	2.28	n/d	n/d	165	149	2.58	n/d	104	165	144
R016	2.62	n/d	n/d	165	n/d	2.62	n/d	n/d	165	n/d
R017	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R018	2.80	n/d	n/d	180	140	2.67	n/d	117	165	136
R019	2.57	n/d	n/d	180	141	2.37	n/d	135	165	135
R020	2.65	n/d	n/d	180	150	2.49	n/d	107	165	n/d
Mean	2.63	n/d	n/d	175	146.4	2.55	n/d	109.9	163.3	141

Table E-2f
Comparison of PT and WATSMART Data for Temporal Matching Posture (xii)
Test Garment L

Trial #	Time (sec)	Left Elbow (degrees)		Left Shoulder (degrees)		Time (sec)	Right Elbow (degrees)		Right Shoulder (degrees)	
		PT	WAT	PT	WAT		PT	WAT	PT	WAT
R011	5.01	90	139	45	n/d	4.91	90	80	45	n/d
R012	4.91	90	79	45	n/d	4.72	90	78	45	n/d
R013	4.72	90	54	45	n/d	4.75	90	84	45	n/d
R014	4.75	90	49	45	n/d	4.16	90	82	45	n/d
R015	4.16	90	n/d	30	n/d	4.37	90	79	45	n/d
R016	4.37	90	n/d	45	n/d	4.37	110	n/d	45	n/d
R017	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d	n/d
R018	4.77	90	91	45	n/d	4.77	90	76	45	n/d
R019	4.53	90	n/d	45	n/d	4.53	90	76	45	n/d
R020	4.43	75	114	45	n/d	4.43	90	78	45	n/d
Mean	4.63	88.3	87.7	43.3	n/d	4.63	92.2	78.9	45	n/d

APPENDIX F

WATSMART WITH POSTURE TAXONOMY DATA AT TEMPORAL MATCHING POSTURES, TEST GARMENTS, FOR ALL TRIALS

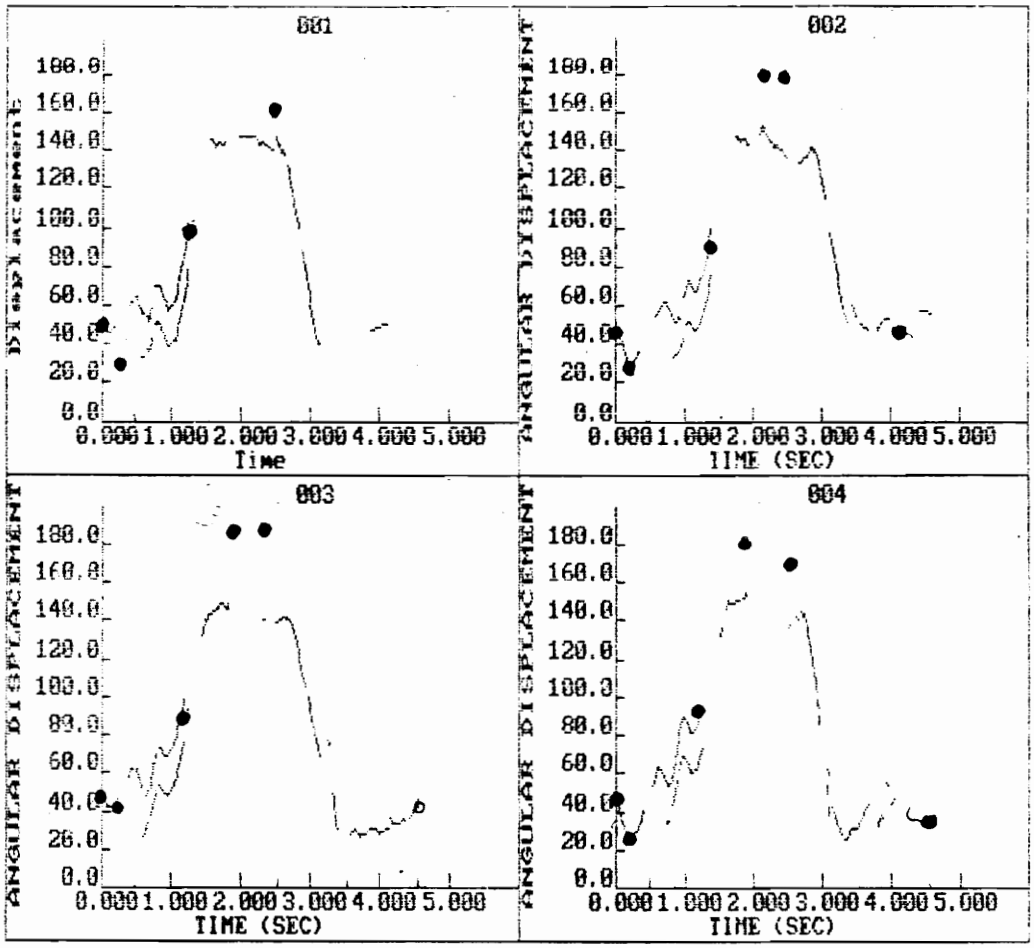

Figure F1a. Left Shoulder

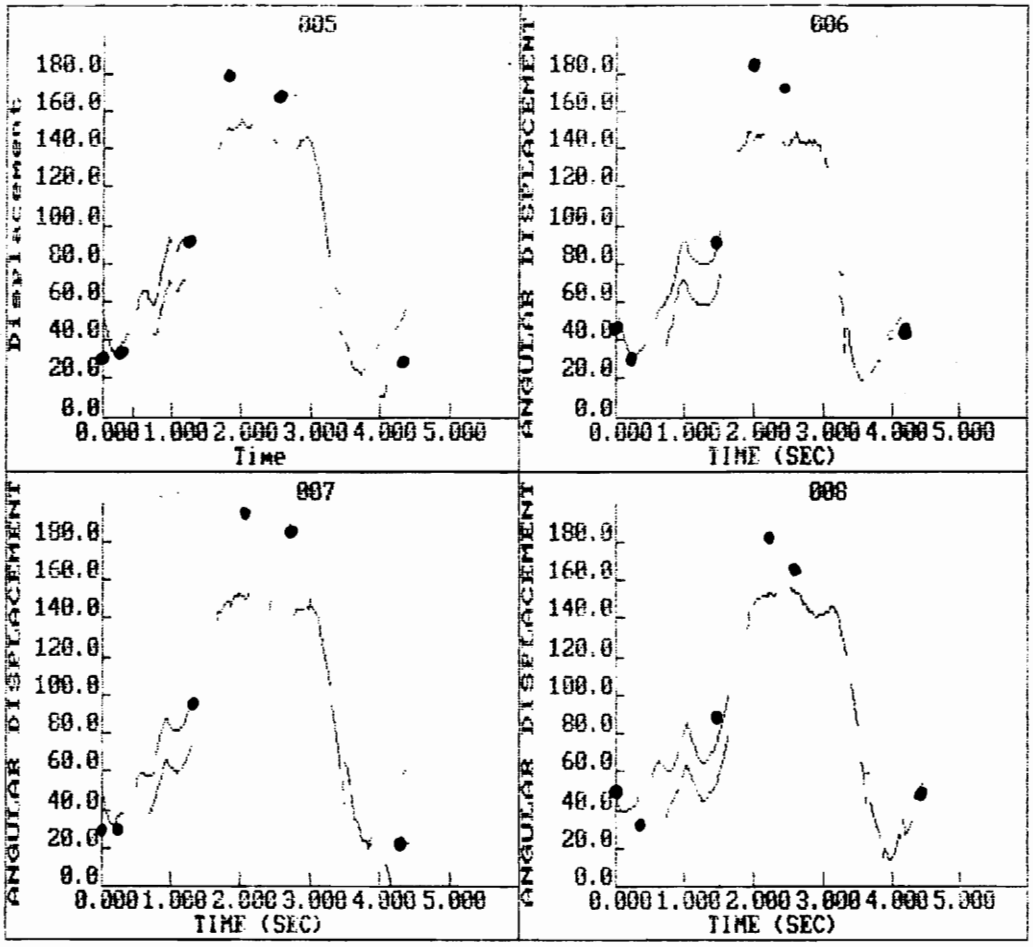

Figure F1b. Left Shoulder

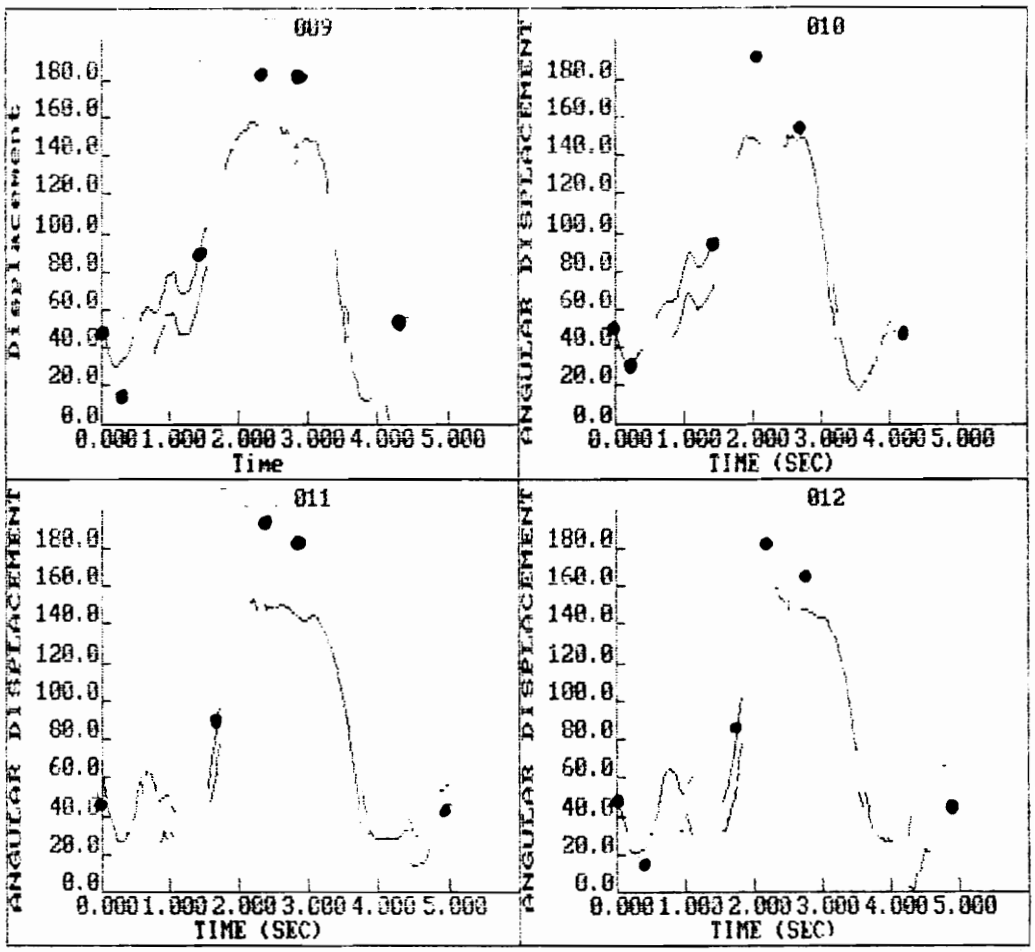

Figure F1c. Left Shoulder

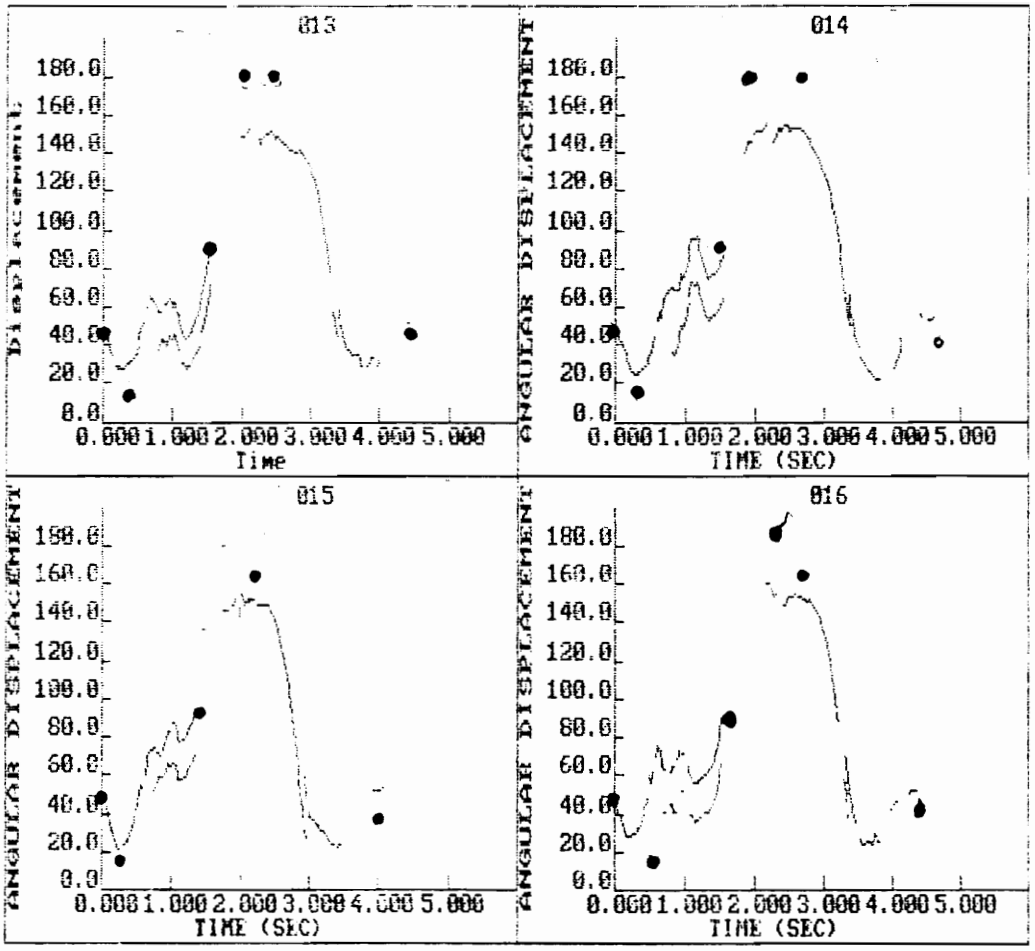

Figure F1d. Left Shoulder

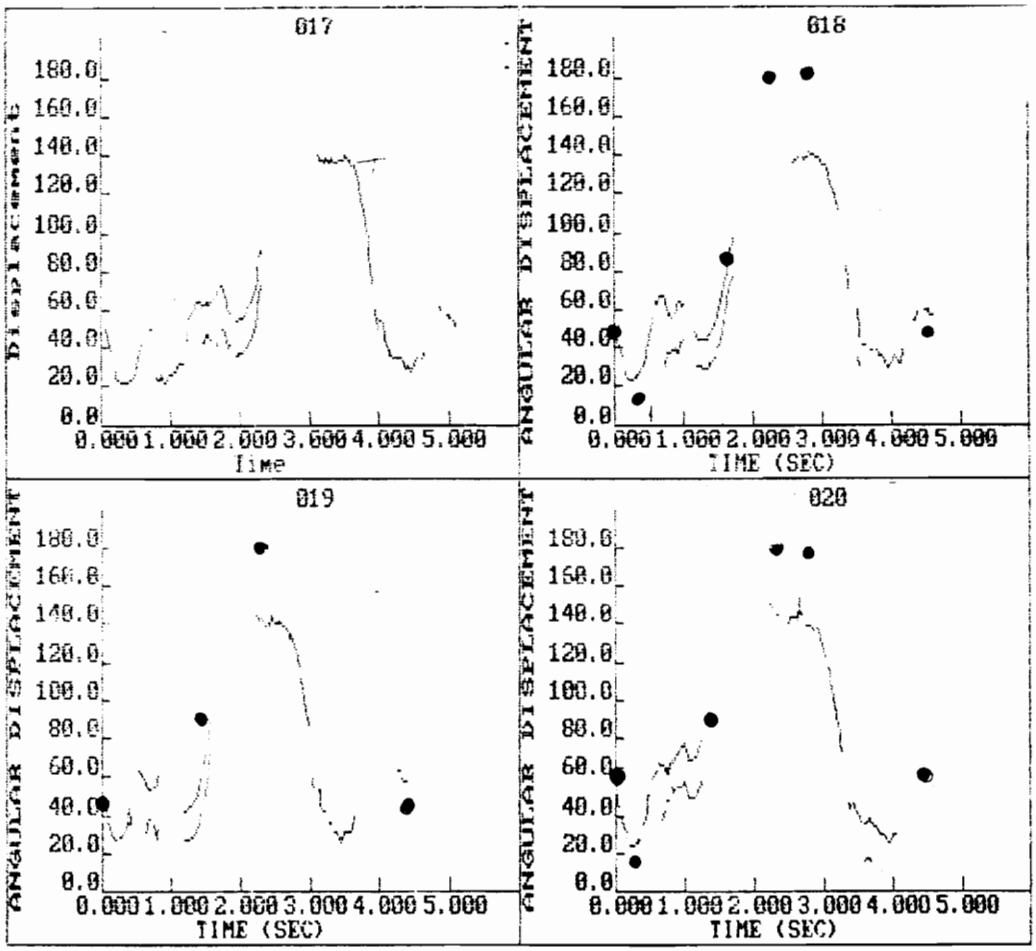

Figure F-1e. Left Shoulder

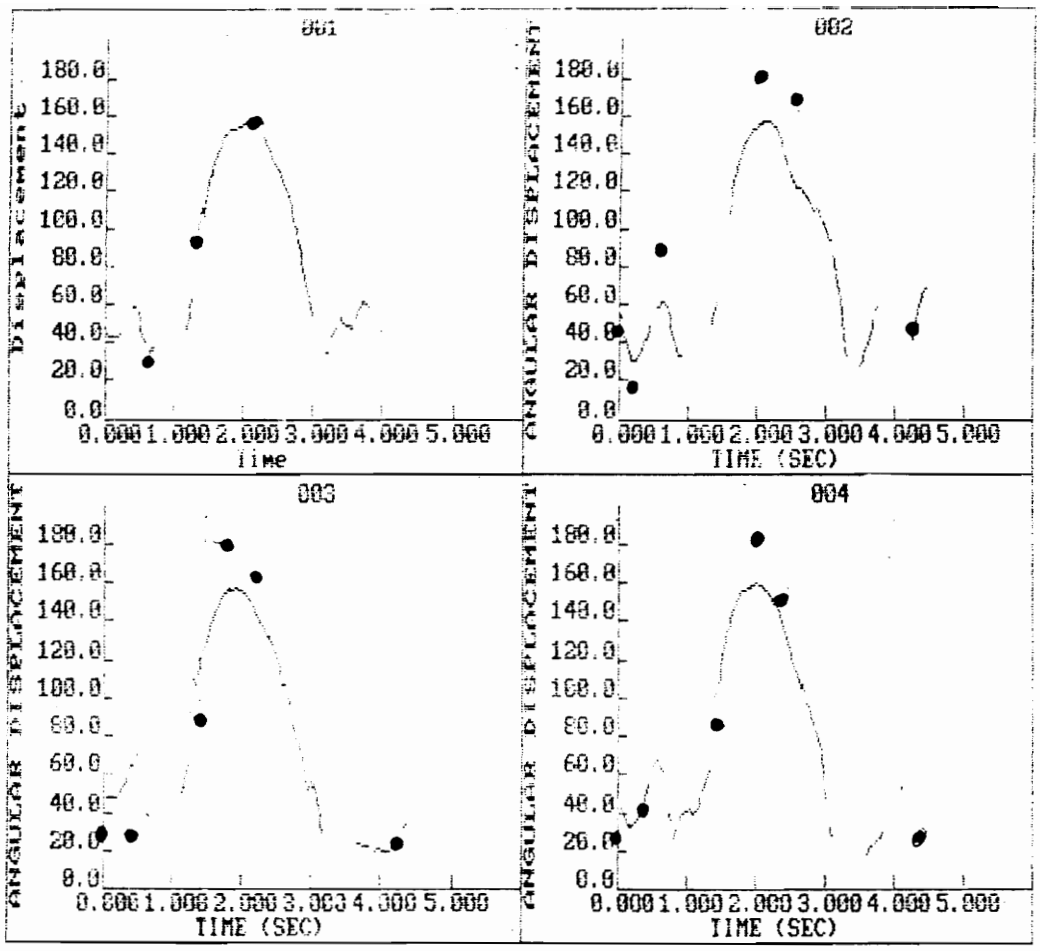

Figure F2a. Right Shoulder

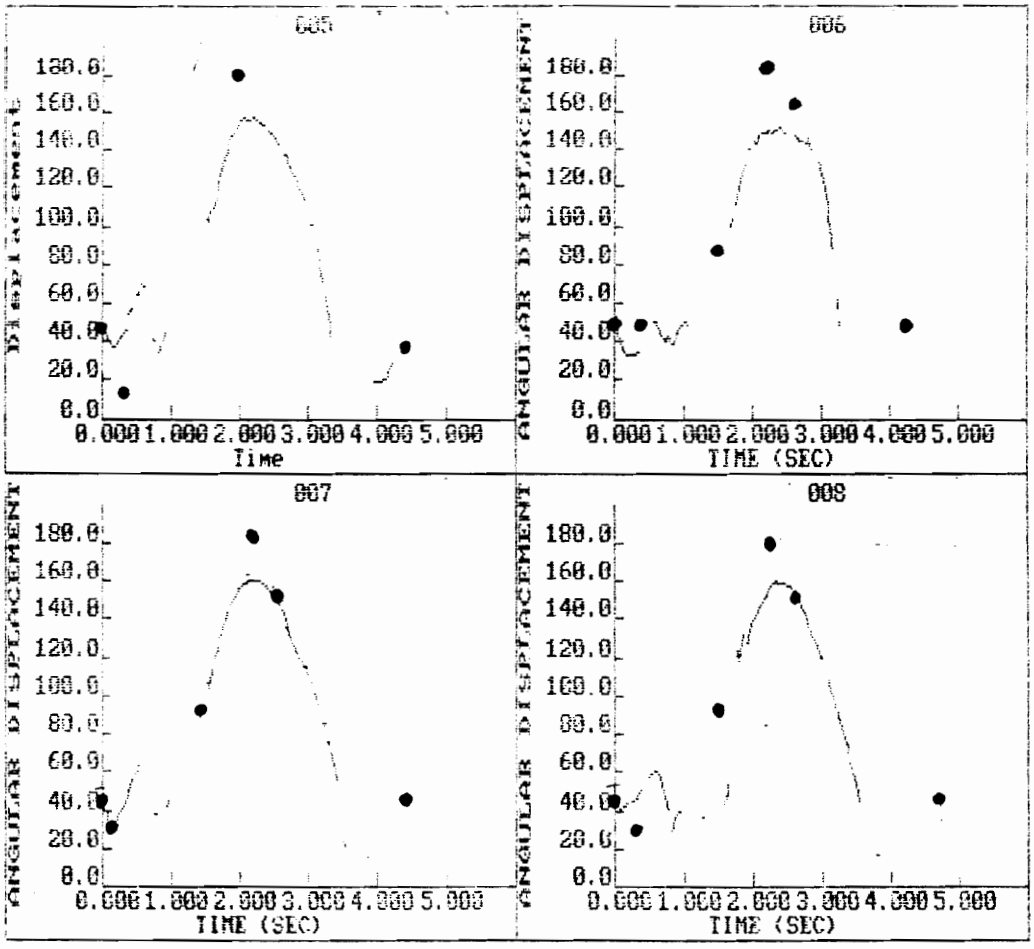

Figure F2b. Right Shoulder

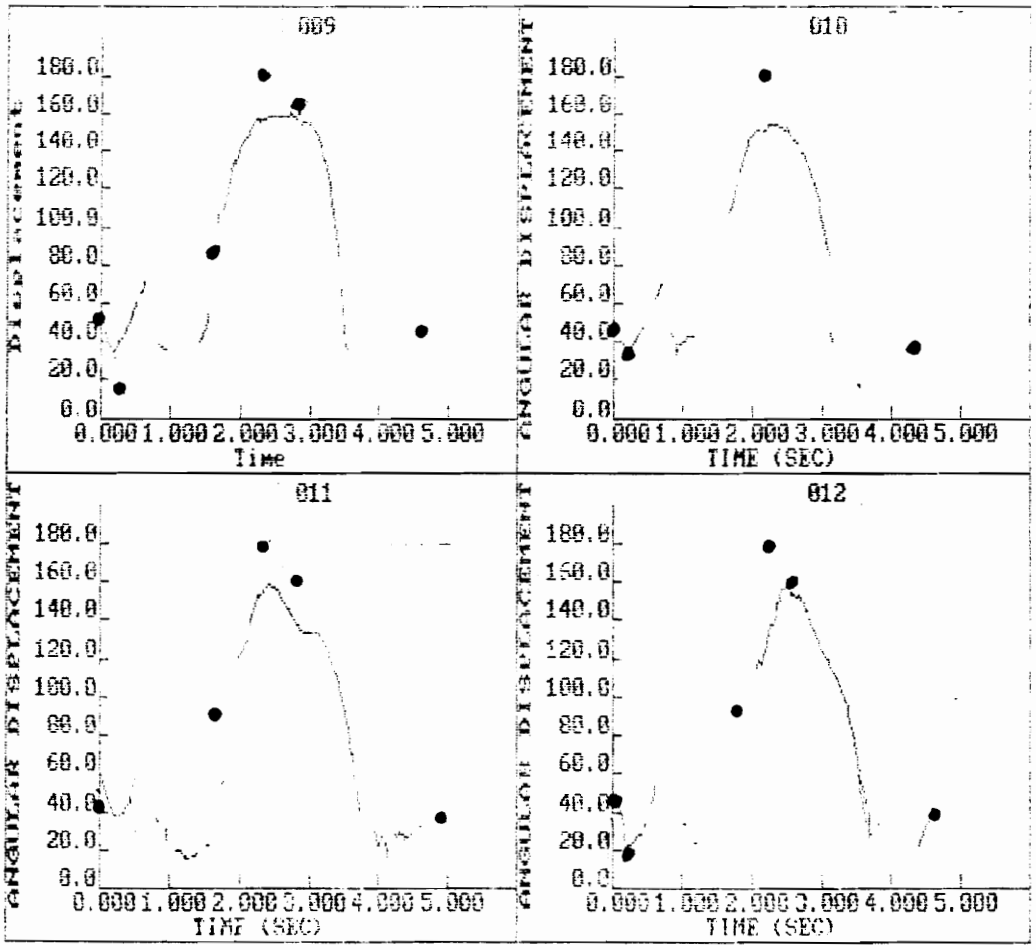

Figure F 2c. Right Shoulder

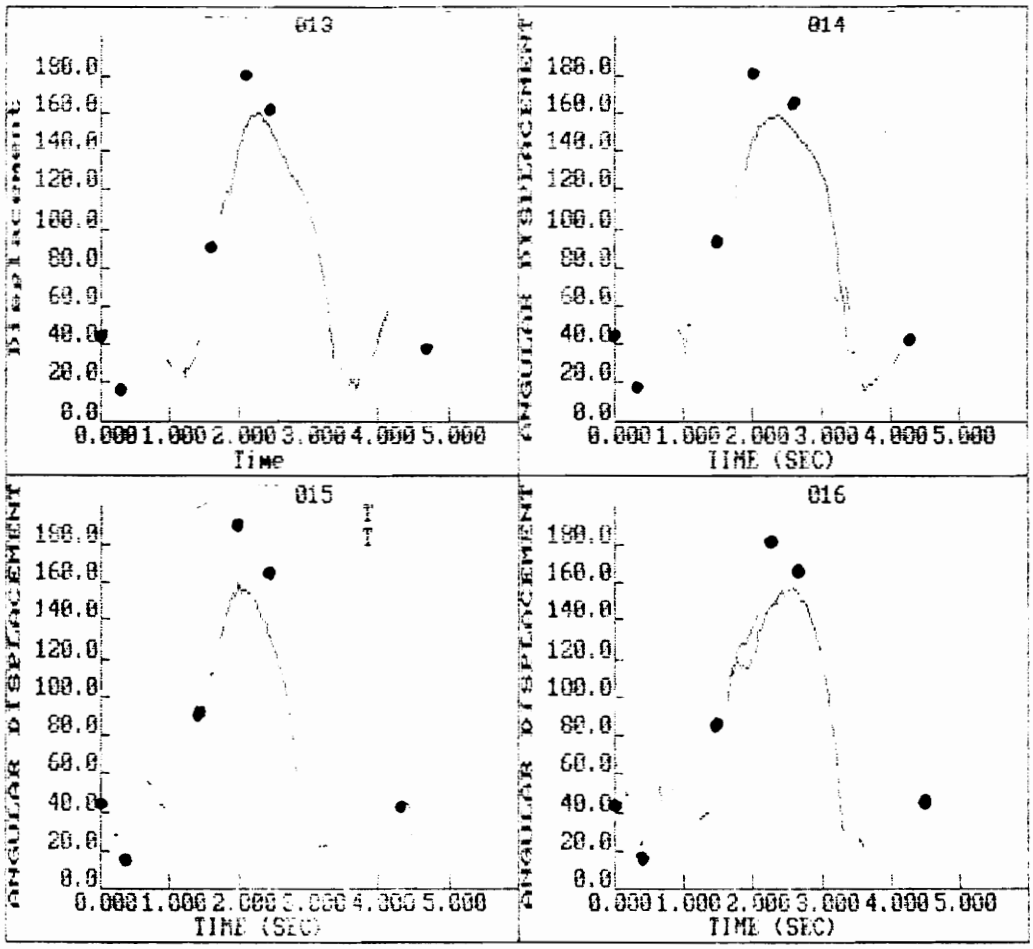

Figure F2d. Right Shoulder

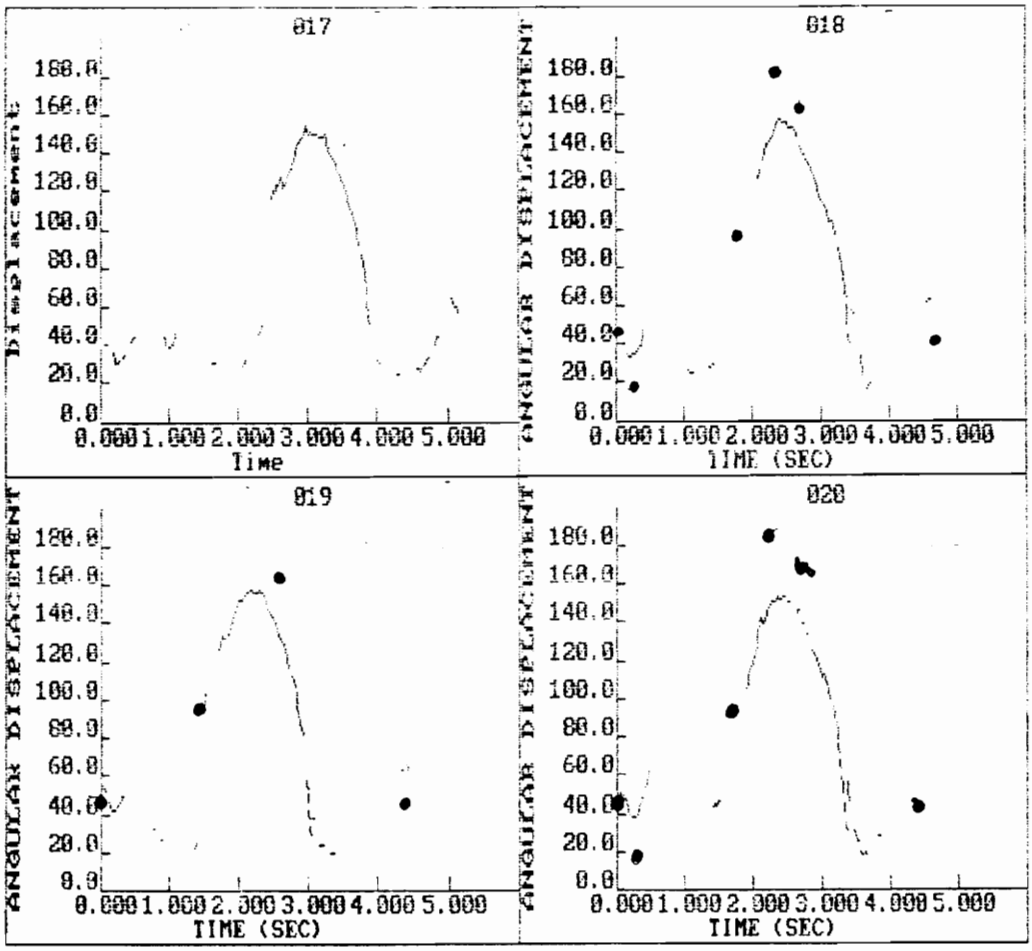

Figure F2e. Right Shoulder

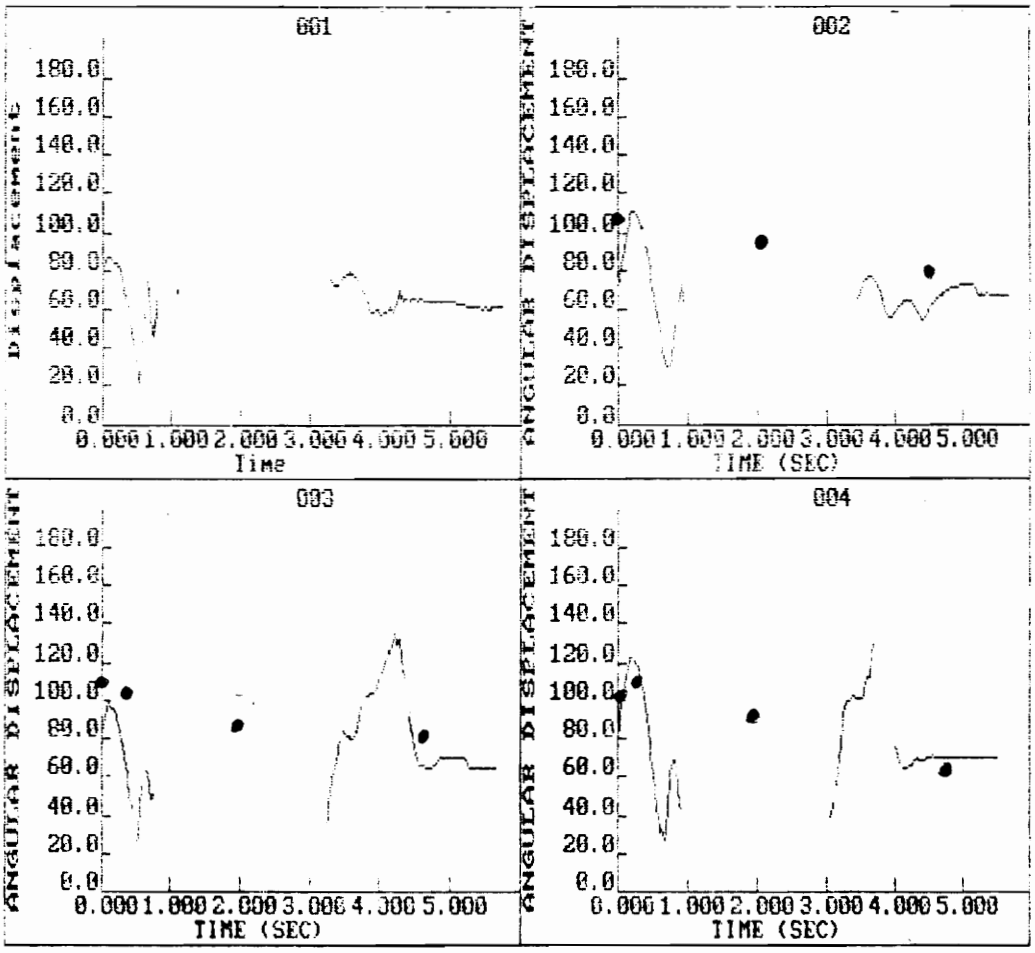

Figure F3a. **Left Elbow**

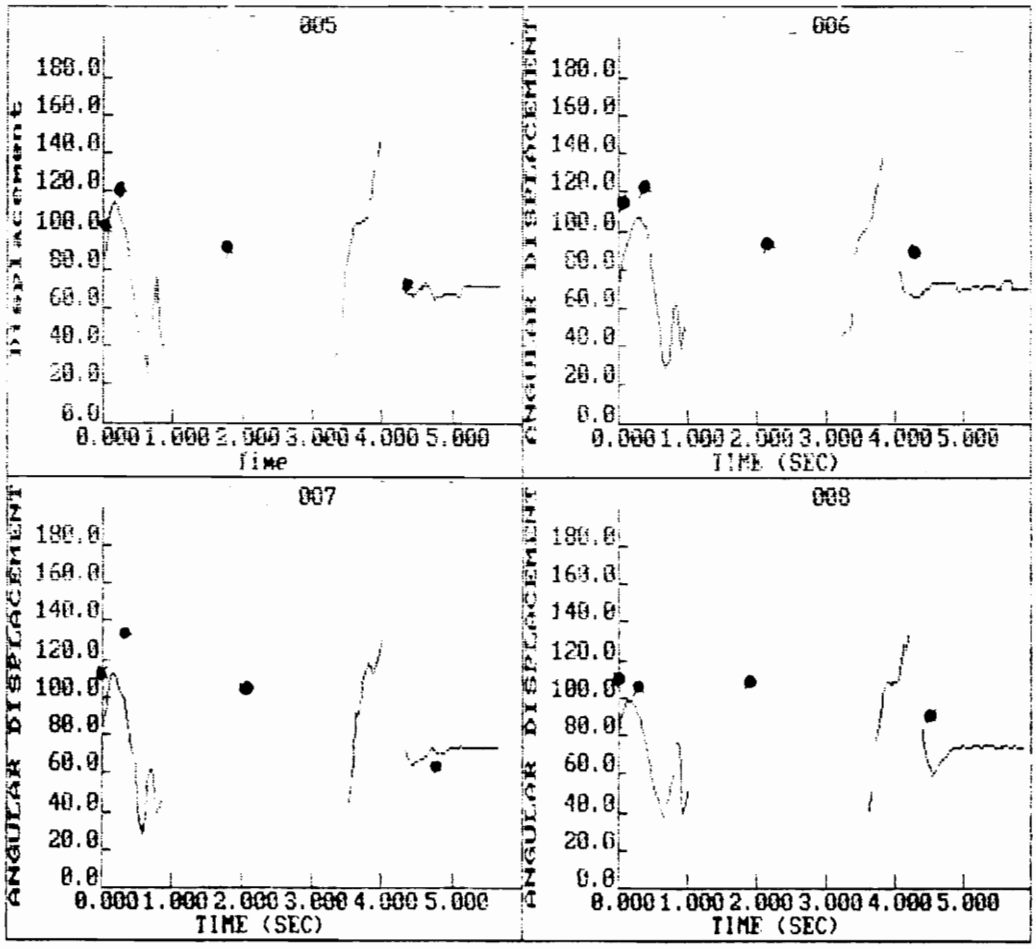

Figure F3b. **Left Elbow**

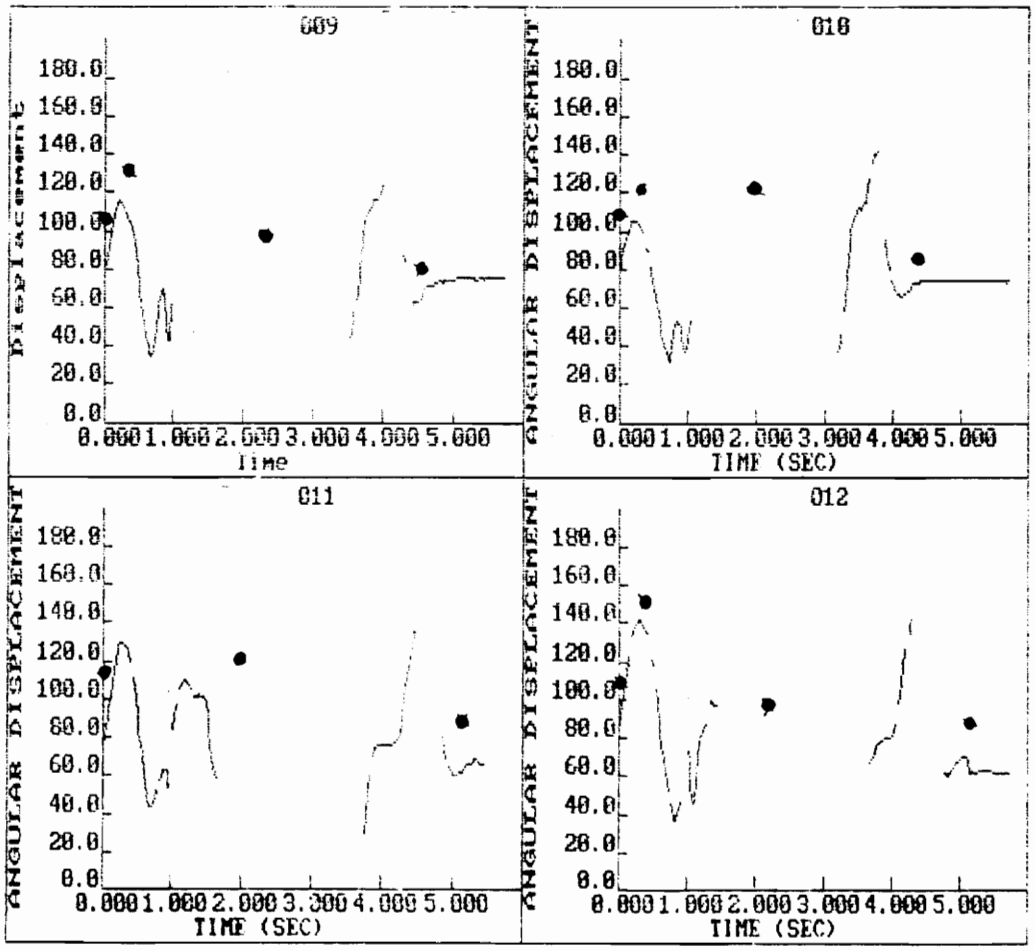

Figure F3c. Left Elbow

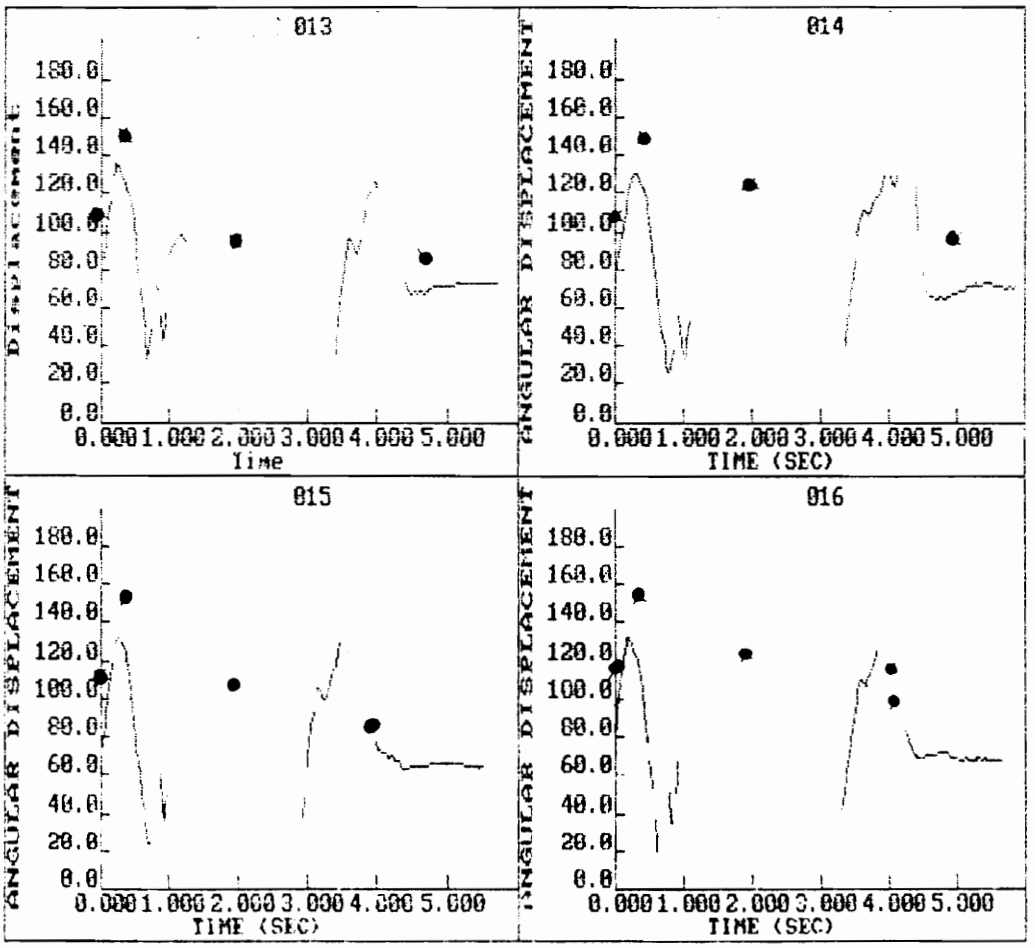

Figure F3d. **Left Elbow**

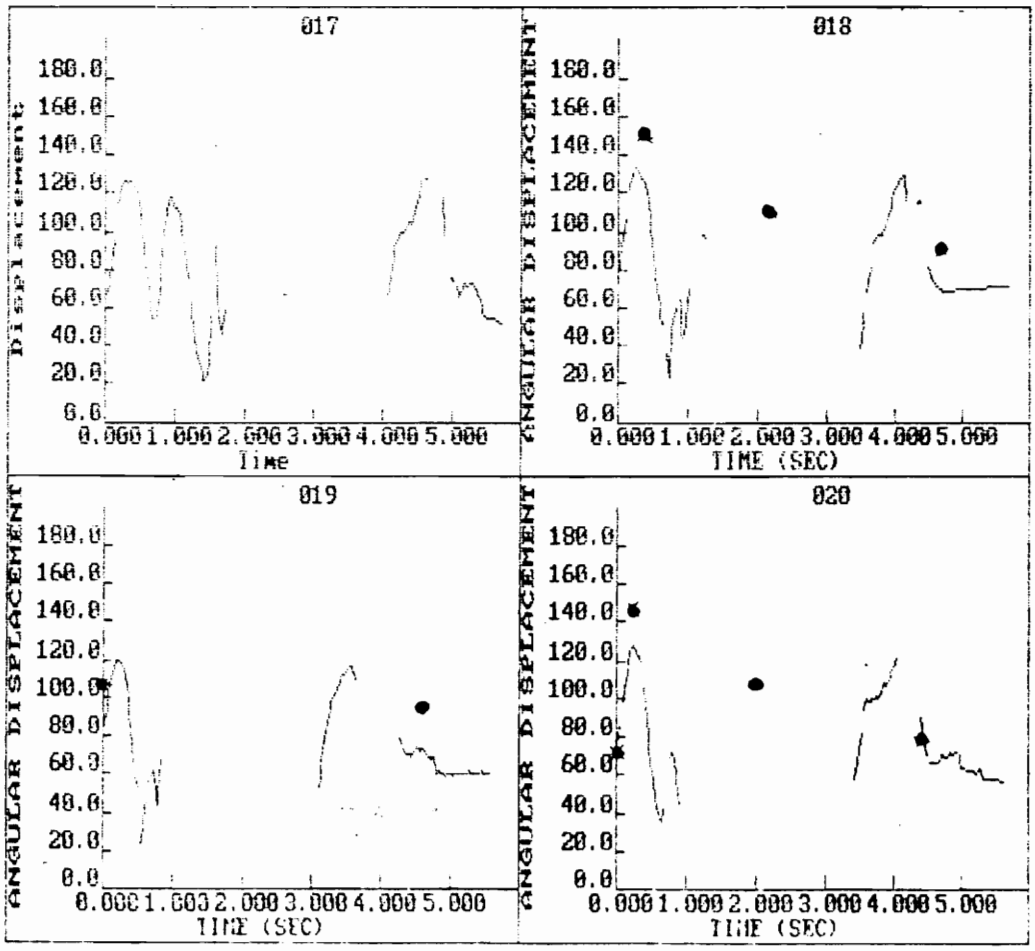

Figure F3e. **Left Elbow**

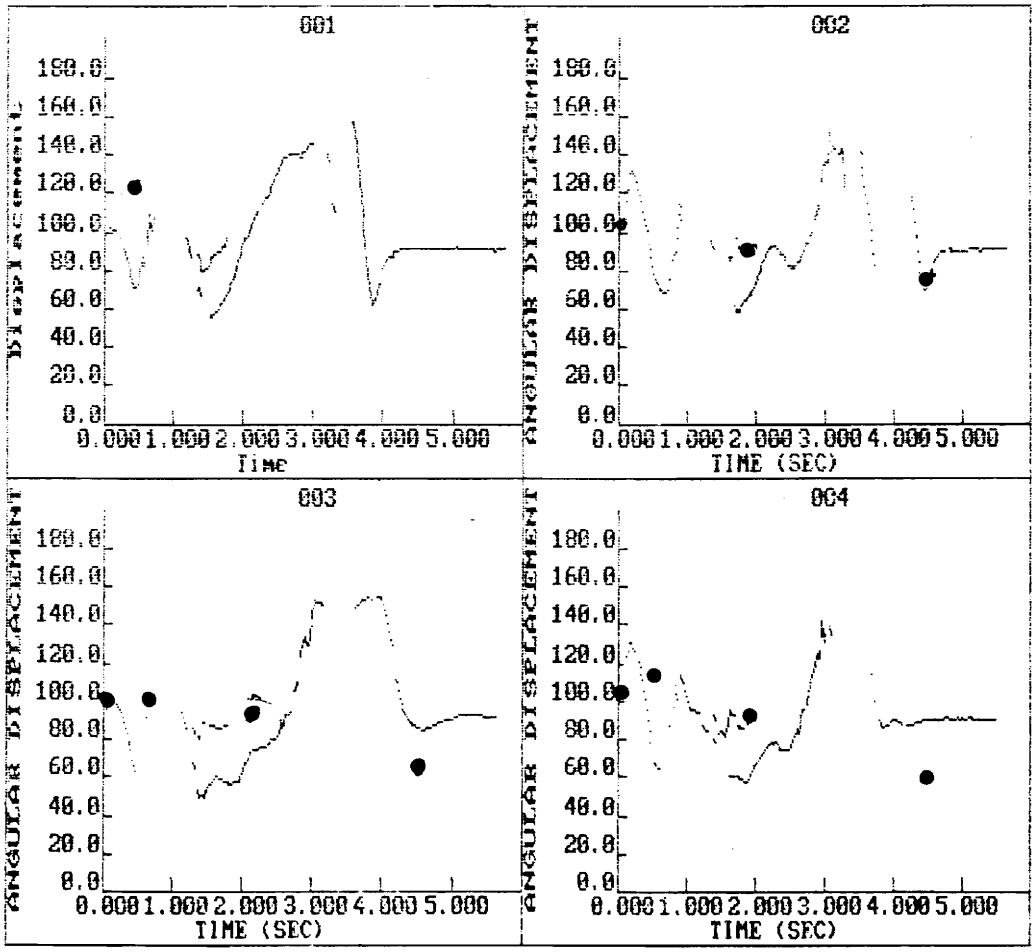

Figure F4a. Right Elbow

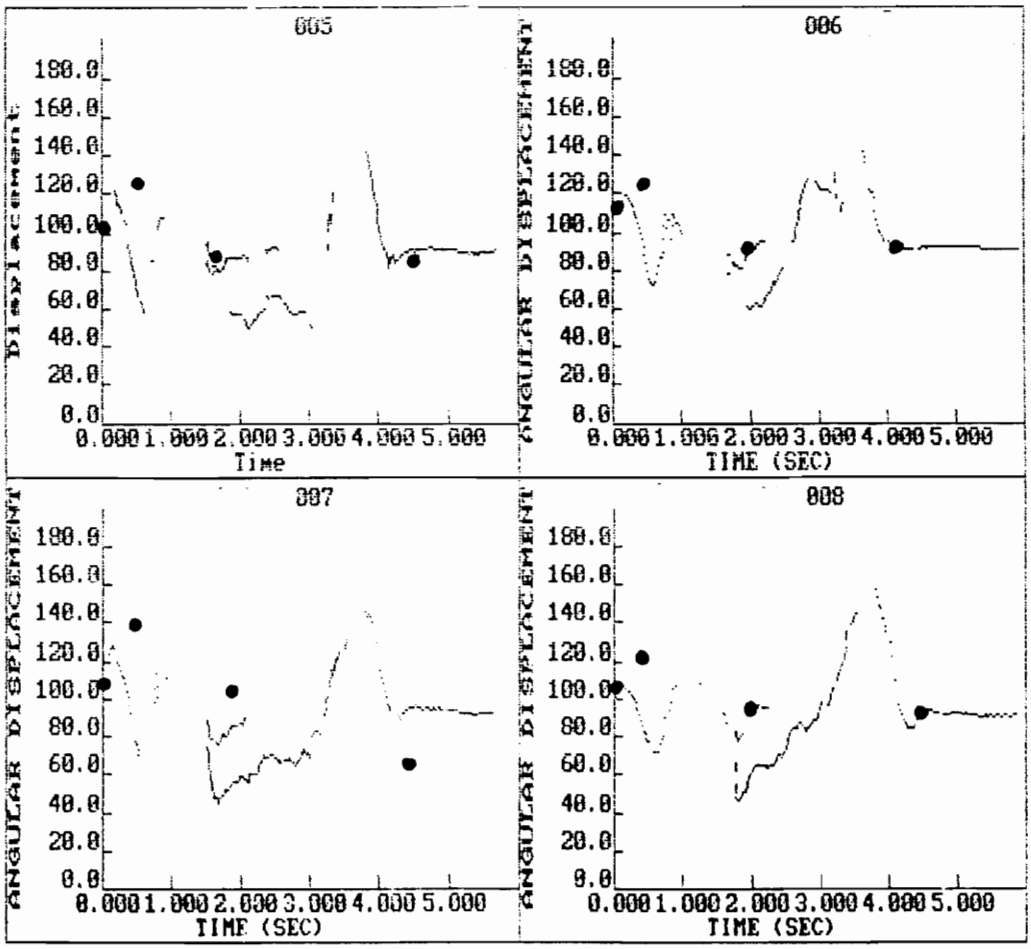

Figure F4b. Right Elbow

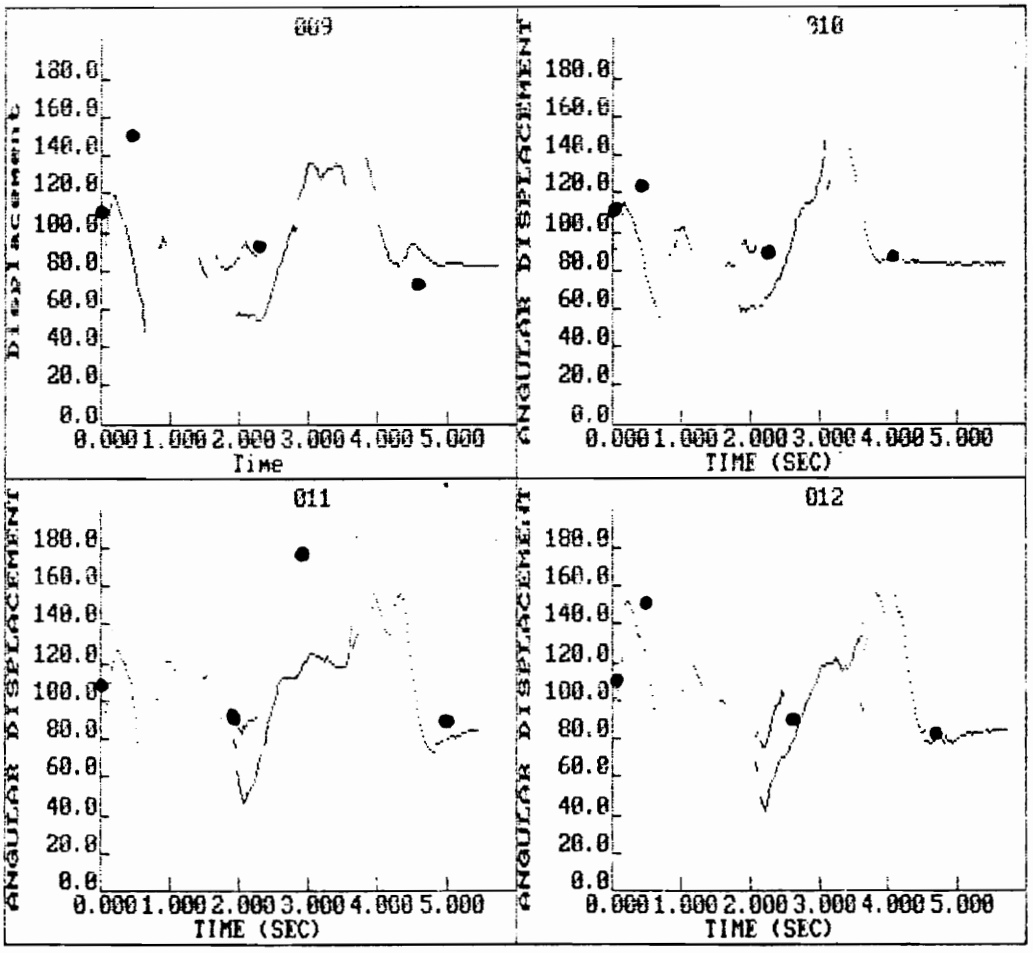

Figure F4c. Right Elbow

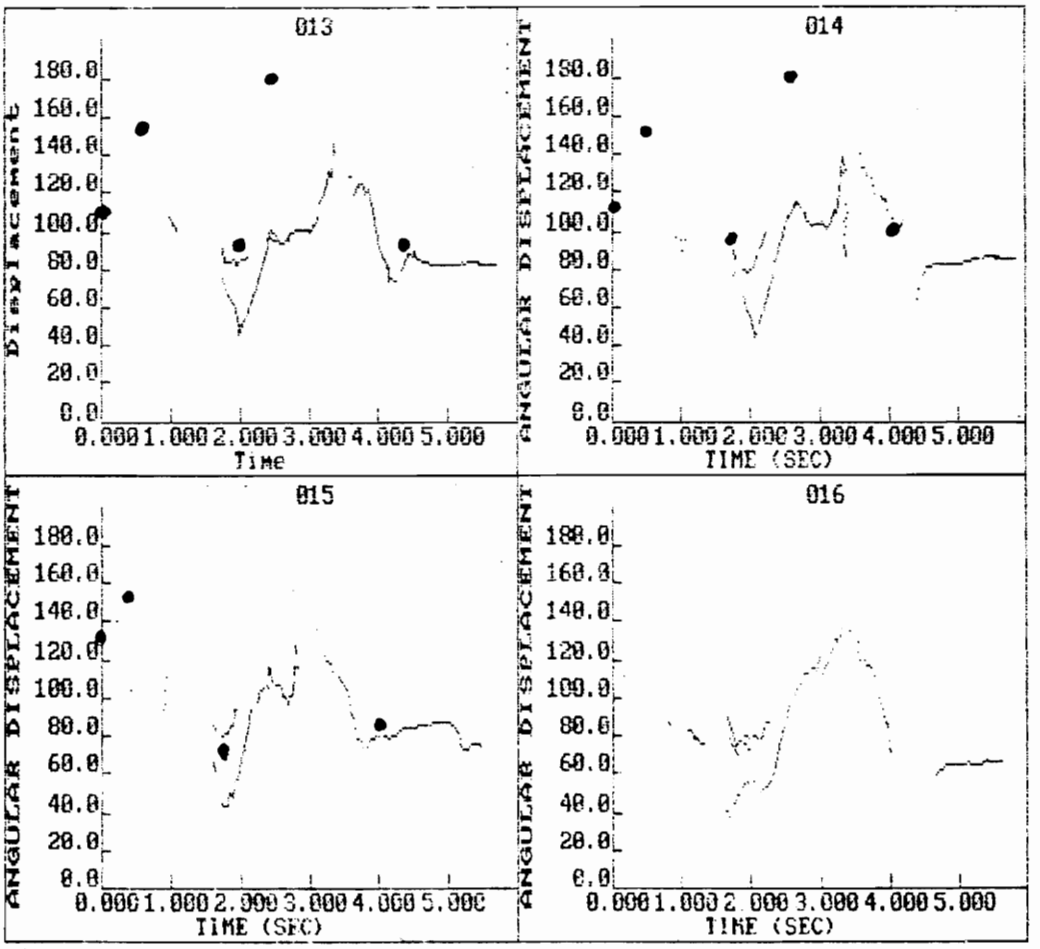

Figure F4d. **Right Elbow**

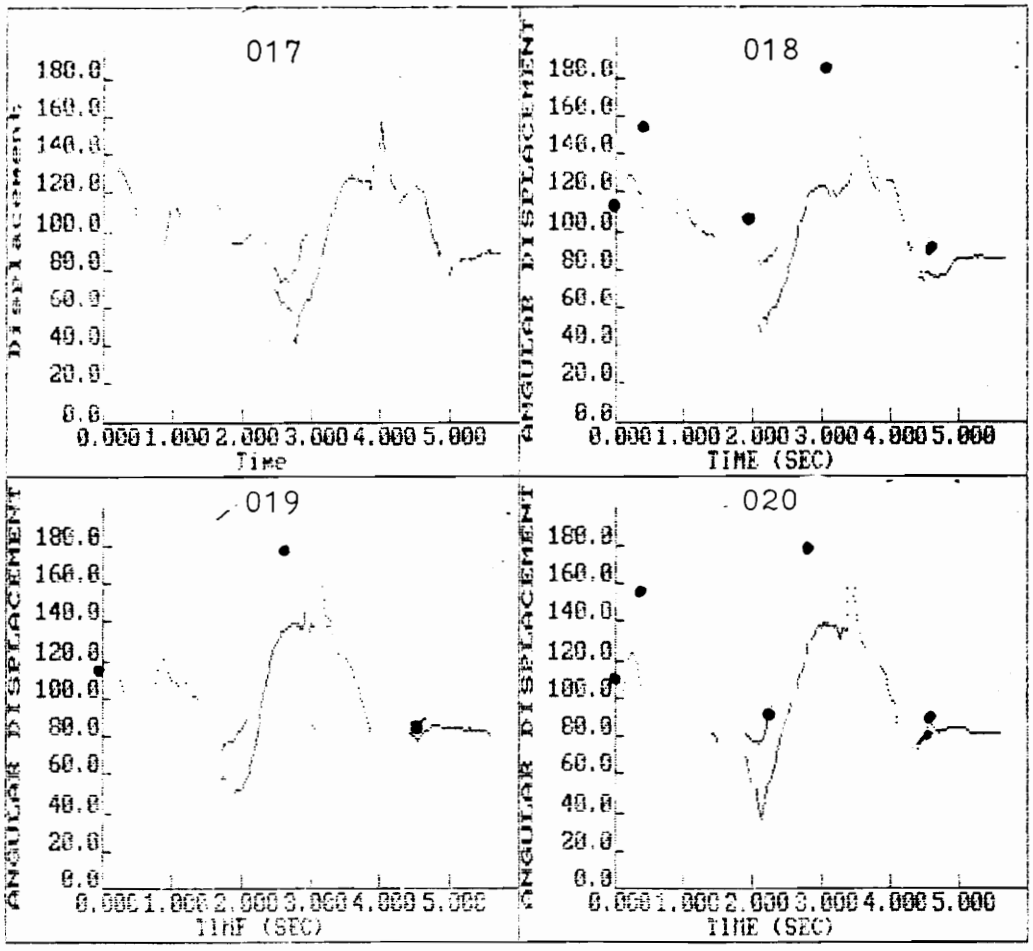

Figure F4e. **Right Elbow**

APPENDIX G
COMPARISON OF WATSMART ANGULAR DISPLACEMENTS BETWEEN TEST AND PURCHASED GARMENTS

Table G-1a
Comparsion of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (i)

Trial #	Time of Occurrence (sec)			Left Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	0.00	0.00	0	59	57	2
R002, -012	0.00	0.00	0	63	68	5
R003, -013	0.00	0.00	0	70	67	3
R004, -014	0.00	0.00	0	69	71	2
R005, -015	0.00	0.00	0	69	62	7
R006, -016	0.00	0.00	0	69	n/d	--
R007, -017	0.00	0.00	0	66	n/d	--
R008, -018	0.00	0.00	0	71	66	0
R009, -019	0.00	0.00	0	66	71	5
R010, -020	0.00	0.00	0	67	64	3
Mean	0.00	0.00		66.9	65.8	1.1

Table G-1b
Comparsion of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (ii)

Trial #	Time of Occurrence (sec)			Left Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	.367	.460	.093	83	63	20
R002, -012	.310	.413	.103	90	123	43
R003, -013	.280	.440	.160	98	118	20
R004, -014	.317	.350	.033	68	125	57
R005, -015	.275	.332	.057	88	62	24
R006, -016	.320	n/d	--	107	n/d	--
R007, -017	.363	n/d	--	92	n/d	--
R008, -018	.307	.395	.088	98	97	3
R009, -019	.337	.320	.017	92	74	18
R010, -020	.400	.325	.075	97	69	28
Mean	.328	.379		91.3	91.4	

Table G-1c
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (vi)

Trial #	Time of Occurrence (sec)			Left Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	1.49	1.82	.33	n/d	91	--
R002, -012	1.37	1.78	.41	n/d	n/d	--
R003, -013	1.39	1.58	.19	n/d	n/d	--
R004, -014	1.23	1.55	.32	75	n/d	--
R005, -015	1.35	1.52	.17	n/d	n/d	--
R006, -016	1.43	n/d	--	n/d	n/d	--
R007, -017	1.47	n/d	--	n/d	n/d	--
R008, -018	1.48	1.67	.19	n/d	n/d	--
R009, -019	1.62	1.52	.10	n/d	n/d	--
R010, -020	1.61	1.41	.20	n/d	n/d	--
Mean	1.44	1.61	.17	n/d	n/d	n/d

Table G-1d
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (vii)

Trial #	Time of Occurrence (sec)			Left Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	2.20	1.96	.24	n/d	91	--
R002, -012	1.91	2.28	.37	n/d	n/d	--
R003, -013	1.88	2.06	.18	n/d	n/d	--
R004, -014	1.91	1.89	.02	n/d	n/d	--
R005, -015	1.76	1.84	.08	n/d	n/d	--
R006, -016	1.97	n/d	--	n/d	n/d	--
R007, -017	2.06	n/d	--	n/d	n/d	--
R008, -018	2.01	2.17	.16	n/d	n/d	--
R009, -019	2.32	n/d	--	n/d	n/d	--
R010, -020	2.28	2.16	.12	n/d	n/d	--
Mean	2.26	2.06	.20	n/d	n/d	n/d

Table G-1e
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (viii)

Trial #	Time of Occurrence (sec)			Left Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	2.63	2.75	.12	n/d	n/d	--
R002, -012	2.24	2.85	.61	n/d	n/d	--
R003, -013	2.37	2.54	.17	n/d	n/d	--
R004, -014	2.34	2.61	.27	n/d	n/d	--
R005, -015	2.43	2.28	.15	n/d	n/d	--
R006, -016	2.40	n/d	--	n/d	n/d	--
R007, -017	2.68	n/d	--	n/d	n/d	--
R008, -018	2.60	2.80	.20	n/d	n/d	--
R009, -019	2.70	2.57	.27	n/d	n/d	--
R010, -020	2.69	2.65	.04	n/d	n/d	--
Mean	2.51	2.63	.12	n/d	n/d	n/d

Table G-1f
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (xii)

Trial #	Time of Occurrence (sec)			Left Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	4.75	5.01	.26	65	139	74
R002, -012	4.22	4.91	.69	65	79	14
R003, -013	4.66	4.72	.06	100	54	46
R004, -014	4.57	4.75	.18	51	49	2
R005, -015	4.36	4.16	.20	123	n/d	--
R006, -016	4.27	n/d	--	50	n/d	--
R007, -017	4.35	n/d	--	117	n/d	--
R008, -018	4.69	4.77	.08	62	91	29
R009, -019	4.69	4.53	.16	45	n/d	--
R010, -020	4.29	4.43	.147	73	114	41
Mean	4.49	4.63	.14	75.1	87.7	12.6

Table G-2a
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (i)

Trial #	Time of Occurrence (sec)			Left Shoulder (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	0.00	0.00	0	51	61	10
R002, -012	0.00	0.00	0	45	48	3
R003, -013	0.00	0.00	0	48	44	4
R004, -014	0.00	0.00	0	52	51	1
R005, -015	0.00	0.00	0	54	47	7
R006, -016	0.00	0.00	0	57	n/d	--
R007, -017	0.00	0.00	0	51	n/d	--
R008, -018	0.00	0.00	0	49	48	1
R009, -019	0.00	0.00	0	53	46	8
R010, -020	0.00	0.00	0	54	46	8
Mean	0.00	0.00		51.4	48.9	2.5

Table G-2b
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (ii)

Trial #	Time of Occurrence (sec)			Left Shoulder (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	.367	.460	.093	51	38	13
R002, -012	.310	.413	.103	34	23	11
R003, -013	.280	.440	.160	n/d	34	--
R004, -014	.317	.350	.033	31	26	5
R005, -015	.275	.332	.057	38	25	13
R006, -016	.320	n/d	--	33	n/d	--
R007, -017	.363	n/d	--	n/d	n/d	--
R008, -018	.307	.395	.088	45	28	13
R009, -019	.337	.320	.017	35	31	4
R010, -020	.400	.325	.075	39	26	13
Mean	.328	.379	.051	38.3	28.9	2.4

Table G-2c
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (vi)

Trial #	Time of Occurrence (sec)			Left Shoulder (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	1.49	1.82	.33	n/d	n/d	--
R002, -012	1.37	1.78	.41	97	92	5
R003, -013	1.39	1.58	.19	n/d	97	--
R004, -014	1.23	1.55	.32	92	93	1
R005, -015	1.35	1.52	.17	n/d	n/d	--
R006, -016	1.43	n/d	--	84	n/d	--
R007, -017	1.47	n/d	--	n/d	n/d	--
R008, -018	1.48	1.67	.19	76	90	14
R009, -019	1.62	1.52	.10	n/d	81	--
R010, -020	1.61	1.41	.20	n/d	n/d	--
Mean	1.44	1.61	.17	87.3	90.6	3.3

Table G-2d
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (vii)

Trial #	Time of Occurrence (sec)			Left Shoulder (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	2.20	1.96	.24	147	n/d	--
R002, -012	1.91	2.28	.37	142	n/d	--
R003, -013	1.88	2.06	.18	150	151	1
R004, -014	1.91	1.89	.02	154	146	8
R005, -015	1.76	1.84	.08	148	148	0
R006, -016	1.97	n/d	--	148	n/d	--
R007, -017	2.06	n/d	--	151	n/d	--
R008, -018	2.01	2.17	.16	149	n/d	--
R009, -019	2.32	n/d	--	n/d	n/d	--
R010, -020	2.28	2.16	.12	n/d	n/d	--
Mean	2.26	2.06	.20	148.6	148.3	.3

Table G-2c
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (viii)

Trial #	Time of Occurrence (sec)			Left Shoulder (degrees)		
	S	L	Diff.	S	L	Dff.
R001, -011	2.63	2.75	.12	137	147	10
R002, -012	2.24	2.85	.61	146	146	0
R003, -013	2.37	2.54	.17	n/d	145	--
R004, -014	2.34	2.61	.27	n/d	153	--
R005, -015	2.43	2.28	.15	143	149	6
R006, -016	2.40	n/d	--	143	n/d	--
R007, -017	2.68	n/d	--	143	n/d	--
R008, -018	2.60	2.80	.20	150	140	1
R009, -019	2.70	2.57	.27	152	141	9
R010, -020	2.69	2.65	.04	148	150	2
Mean	2.51	2.63	.12	145.6	146.4	.8

Table G-2f
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (xii)

Trial #	Time of Occurrence (sec)			Left Shoulder (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	4.75	5.01	.26	n/d	n/d	--
R002, -012	4.22	4.91	.69	49	n/d	--
R003, -013	4.66	4.72	.06	n/d	n/d	--
R004, -014	4.57	4.75	.18	n/d	n/d	--
R005, -015	4.36	4.16	.20	57	n/d	--
R006, -016	4.27	n/d	--	n/d	n/d	--
R007, -017	4.35	n/d	--	n/d	n/d	--
R008, -018	4.69	4.77	.08	n/d	n/d	--
R009, -019	4.69	4.53	.16	n/d	n/d	--
R010, -020	4.29	4.43	.147	n/d	n/d	--
Mean	4.49	4.63	.14	55.3	n/d	n/d

Table G-3a
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (i)

Trial #	Time of Occurrence (sec)			Right Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	0.00	0.00	0	96	85	11
R002, -012	0.00	0.00	0	115	90	25
R003, -013	0.00	0.00	0	95	n/d	--
R004, -014	0.00	0.00	0	123	n/d	--
R005, -015	0.00	0.00	0	123	n/d	--
R006, -016	0.00	0.00	0	113	n/d	--
R007, -017	0.00	0.00	0	115	n/d	--
R008, -018	0.00	0.00	0	98	n/d	--
R009, -019	0.00	0.00	0	91	n/d	--
R010, -020	0.00	0.00	0	107	83	24
Mean	0.00	0.00		107.6	86	21.6

Table G-3b
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (ii)

Trial #	Time of Occurrence (sec)			Right Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	.367	.460	.093	n/d	101	--
R002, -012	.310	.413	.103	117	132	15
R003, -013	.280	.440	.160	91	n/d	--
R004, -014	.317	.350	.033	118	n/d	--
R005, -015	.275	.332	.057	111	n/d	--
R006, -016	.320	n/d	--	110	n/d	--
R007, -017	.363	n/d	--	100	n/d	--
R008, -018	.307	.395	.088	100	107	7
R009, -019	.337	.320	.017	104	102	2
R010, -020	.400	.325	.075	95	117	22
Mean	.328	.379	.51	155.3	111.8	43.5

Table G-3c
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (vi)

Trial #	Time of Occurrence (sec)			Right Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	1.49	1.82	.33	n/d	57	--
R002, -012	1.37	1.78	.41	93	92	1
R003, -013	1.39	1.58	.19	n/d	81	--
R004, -014	1.23	1.55	.32	n/d	89	--
R005, -015	1.35	1.52	.17	n/d	n/d	--
R006, -016	1.43	n/d	--	n/d	n/d	--
R007, -017	1.47	n/d	--	n/d	75	--
R008, -018	1.48	1.67	.19	n/d	n/d	--
R009, -019	1.62	1.52	.10	86	79	7
R010, -020	1.61	1.41	.20	82	76	6
Mean	1.44	1.61	.17	60.3	78.4	18.1

Table G-3d
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (vii)

Trial #	Time of Occurrence (sec)			Right Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	2.20	1.96	.24	110	72	38
R002, -012	1.91	2.28	.37	67	56	12
R003, -013	1.88	2.06	.18	57	54	3
R004, -014	1.91	1.89	.02	59	67	8
R005, -015	1.76	1.84	.08	n/d	46	--
R006, -016	1.97	n/d	--	61	n/d	--
R007, -017	2.06	n/d	--	57	n/d	--
R008, -018	2.01	2.17	.16	63	55	8
R009, -019	2.32	n/d	--	55	n/d	--
R010, -020	2.28	2.16	.12	68	46	22
Mean	2.26	2.06	.20	66.3	56.6	4.7

Table G-3c
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (viii)

Trial #	Time of Occurrence (sec)			Right Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	2.63	2.75	.12	140	112	28
R002, -012	2.24	2.85	.61	93	102	9
R003, -013	2.37	2.54	.17	77	95	18
R004, -014	2.34	2.61	.27	76	107	31
R005, -015	2.43	2.28	.15	65	104	39
R006, -016	2.40	n/d	--	77	n/d	--
R007, -017	2.68	n/d	--	68	n/d	--
R008, -018	2.60	2.80	.20	84	117	33
R009, -019	2.70	2.57	.27	95	135	40
R010, -020	2.69	2.65	.04	106	107	1
Mean	2.51	2.63	.12	88.1	109.9	21.8

Table G-3f
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (xii)

Trial #	Time of Occurrence (sec)			Right Elbow (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	4.75	5.01	.26	91	80	9
R002, -012	4.22	4.91	.69	118	78	40
R003, -013	4.66	4.72	.06	185	84	101
R004, -014	4.57	4.75	.18	90	82	8
R005, -015	4.36	4.16	.20	93	79	14
R006, -016	4.27	n/d	--	91	n/d	--
R007, -017	4.35	n/d	--	93	n/d	--
R008, -018	4.69	4.77	.08	92	76	16
R009, -019	4.69	4.53	.16	87	78	9
R010, -020	4.29	4.43	.147	83	77	6
Mean	4.49	4.63	.14	91.9	78.9	13.0

Table G-4a
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (i)

Trial #	Time of Occurrence (sec)			Right Shoulder (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	0.00	0.00	0	44	54	10
R002, -012	0.00	0.00	0	54	52	2
R003, -013	0.00	0.00	0	48	n/d	--
R004, -014	0.00	0.00	0	51	n/d	--
R005, -015	0.00	0.00	0	44	n/d	--
R006, -016	0.00	0.00	0	55	n/d	--
R007, -017	0.00	0.00	0	42	n/d	--
R008, -018	0.00	0.00	0	44	n/d	--
R009, -019	0.00	0.00	0	55	55	0
R010, -020	0.00	0.00	0	54	63	9
Mean	0.00	0.00	0	44.1	56.0	1.9

Table G-4b
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (ii)

Trial #	Time of Occurrence (sec)			Right Shoulder (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	.367	.460	.093	n/d	51	--
R002, -012	.310	.413	.103	34	29	5
R003, -013	.280	.440	.160	53	n/d	--
R004, -014	.317	.350	.033	39	39	0
R005, -015	.275	.332	.057	43	n/d	--
R006, -016	.320	n/d	--	357	n/d	--
R007, -017	.363	n/d	--	49	n/d	--
R008, -018	.307	.395	.088	46	47	1
R009, -019	.337	.320	.017	45	50	5
R010, -020	.400	.325	.075	46	42	4
Mean	.328	.379	.51	43.3	43.0	0

Table G-4c
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (vi)

Trial #	Time of Occurrence (sec)			Right Shoulder (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	1.49	1.82	.33	127	n/d	--
R002, -012	1.37	1.78	.41	54	53	1
R003, -013	1.39	1.58	.19	119	n/d	--
R004, -014	1.23	1.55	.32	52	n/d	--
R005, -015	1.35	1.52	.17	n/d	n/d	--
R006, -016	1.43	n/d	--	n/d	n/d	--
R007, -017	1.47	n/d	--	106	n/d	--
R008, -018	1.48	1.67	.19	n/d	n/d	--
R009, -019	1.62	1.52	.10	103	n/d	--
R010, -020	1.61	1.41	.20	105	43	62
Mean	1.44	1.61	.17	95.1	n/d	n/d

Table G-4d
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (vii)

Trial #	Time of Occurrence (sec)			Right Shoulder (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	2.20	1.96	.24	155	118	37
R002, -012	1.91	2.28	.37	152	138	14
R003, -013	1.88	2.06	.18	157	151	6
R004, -014	1.91	1.89	.02	157	128	29
R005, -015	1.76	1.84	.08	136	146	10
R006, -016	1.97	n/d	--	141	n/d	--
R007, -017	2.06	n/d	--	158	n/d	--
R008, -018	2.01	2.17	.16	143	138	5
R009, -019	2.32	n/d	--	157	n/d	--
R010, -020	2.28	2.16	.12	155	139	--
Mean	2.26	2.06	.20	150.9	135.4	15.5

Table G-4c
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (viii)

Trial #	Time of Occurrence (sec)			Right Shoulder (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	2.63	2.75	.12	117	141	24
R002, -012	2.24	2.85	.61	155	137	18
R003, -013	2.37	2.54	.17	132	144	12
R004, -014	2.34	2.61	.27	144	150	6
R005, -015	2.43	2.28	.15	149	144	5
R006, -016	2.40	n/d	--	152	n/d	--
R007, -017	2.68	n/d	--	137	n/d	--
R008, -018	2.60	2.80	.20	148	136	12
R009, -019	2.70	2.57	.27	161	135	26
R010, -020	2.69	2.65	.04	140	n/d	--
Mean	2.51	2.63	.12	143.9	141	2.9

Table G-4f
Comparison of WATSMART Angular Displacements
for Test Garment S and Test Garment L
for Temporal Matching Posture (xii)

Trial #	Time of Occurrence (sec)			Right Shoulder (degrees)		
	S	L	Diff.	S	L	Diff.
R001, -011	4.75	5.01	.26	n/d	n/d	--
R002, -012	4.22	4.91	.69	n/d	n/d	--
R003, -013	4.66	4.72	.06	n/d	n/d	--
R004, -014	4.57	4.75	.18	n/d	n/d	--
R005, -015	4.36	4.16	.20	n/d	n/d	--
R006, -016	4.27	n/d	--	n/d	n/d	--
R007, -017	4.35	n/d	--	n/d	n/d	--
R008, -018	4.69	4.77	.08	n/d	n/d	--
R009, -019	4.69	4.53	.16	n/d	n/d	--
R010, -020	4.29	4.43	.147	n/d	n/d	--
Mean	4.49	4.63	.14	n/d	n/d	n/d

APPENDIX H
INTER-TRIAL CONSISTENCY GRAPHS OF WATSMART DATA

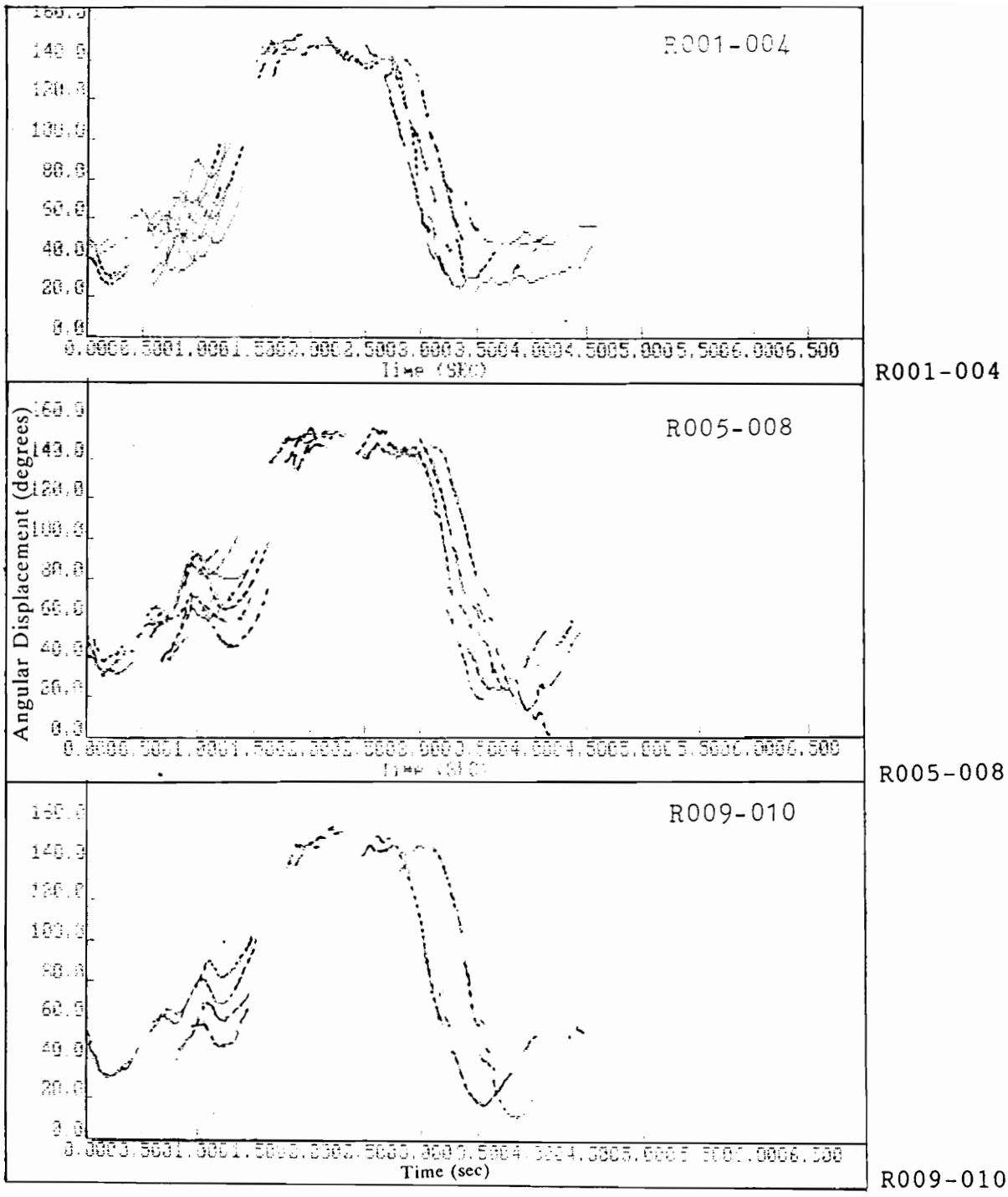

Figure H1a. Left Shoulder

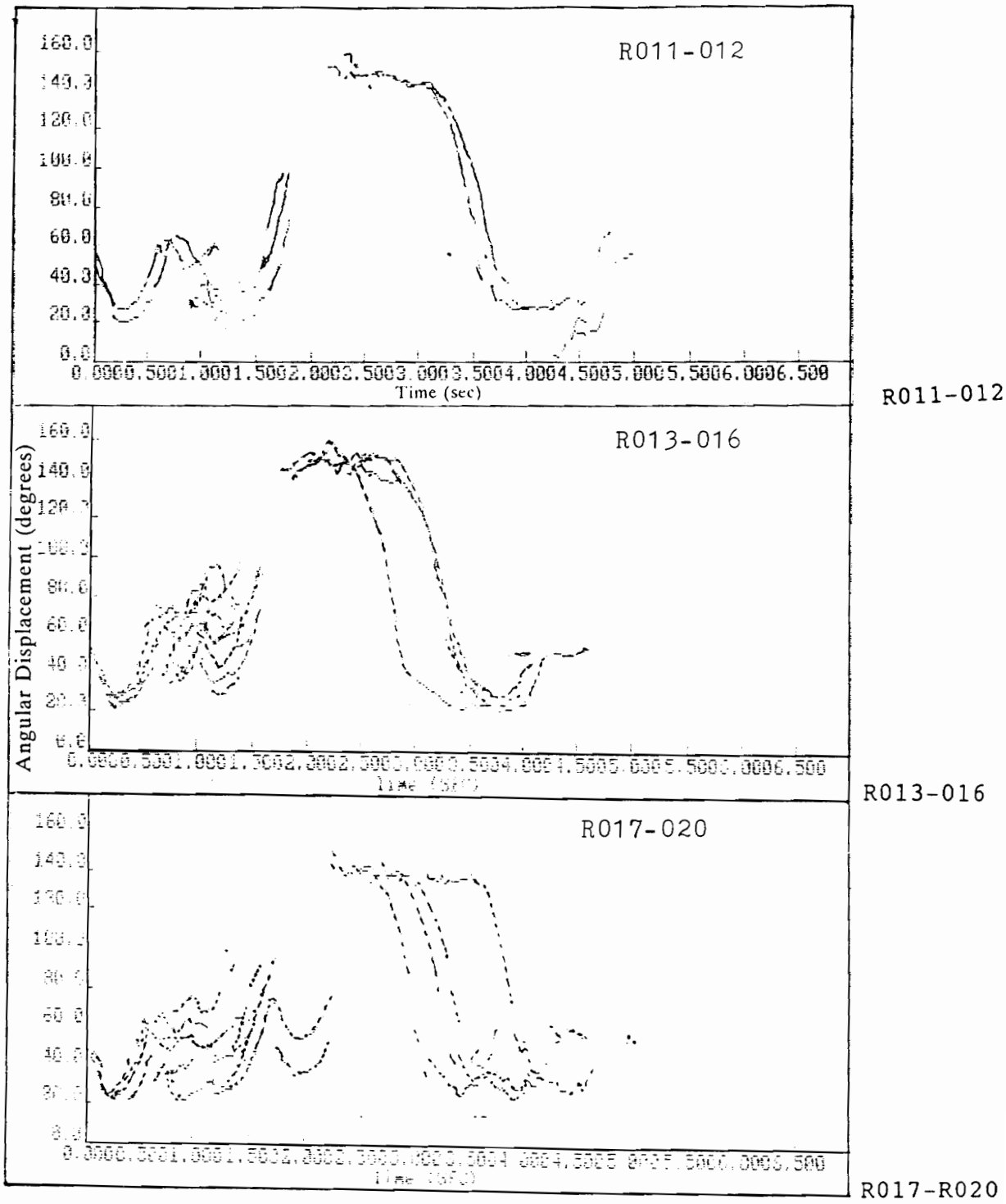

Figure H1b. Left Shoulder

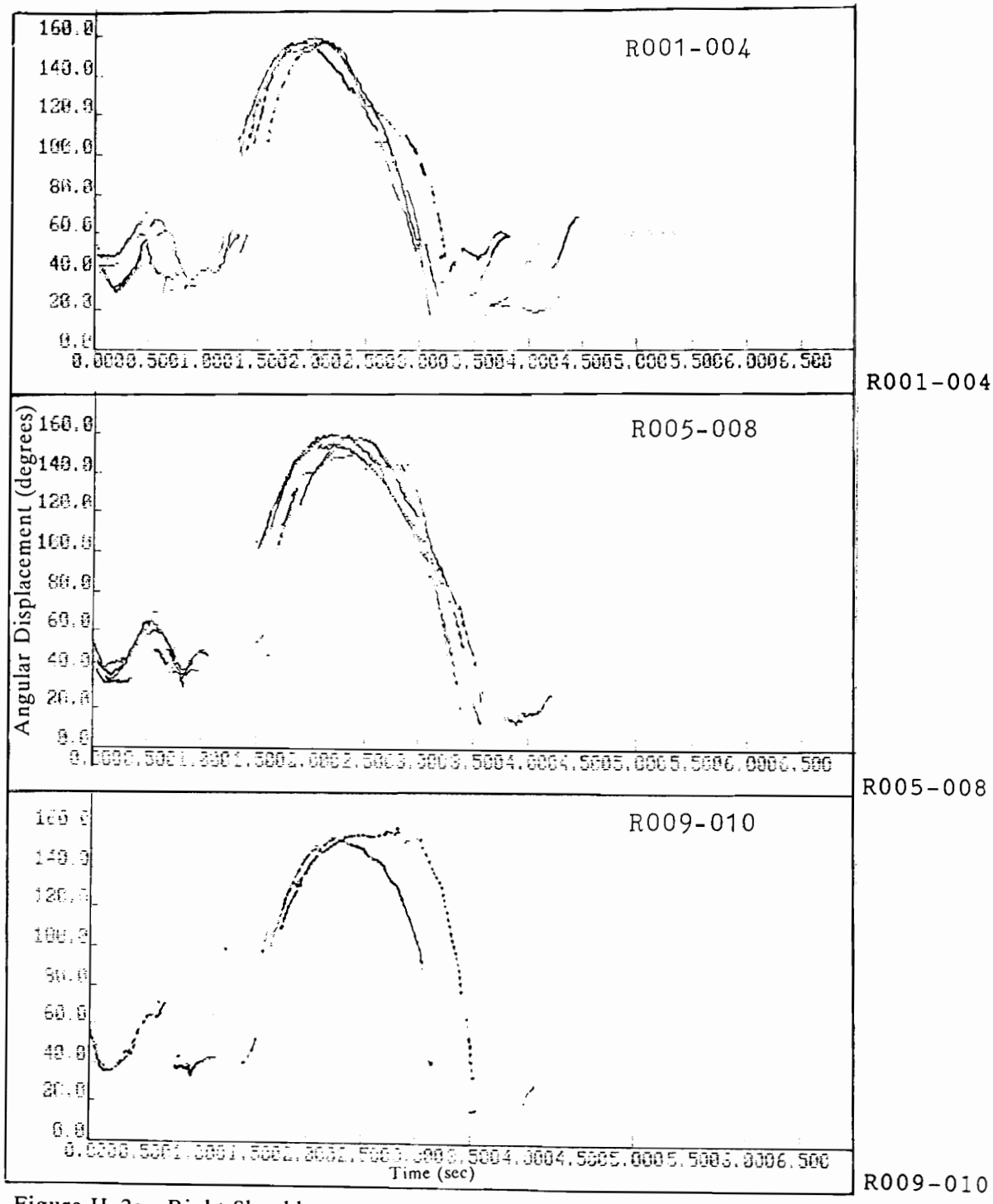

Figure H-2a. Right Shoulder

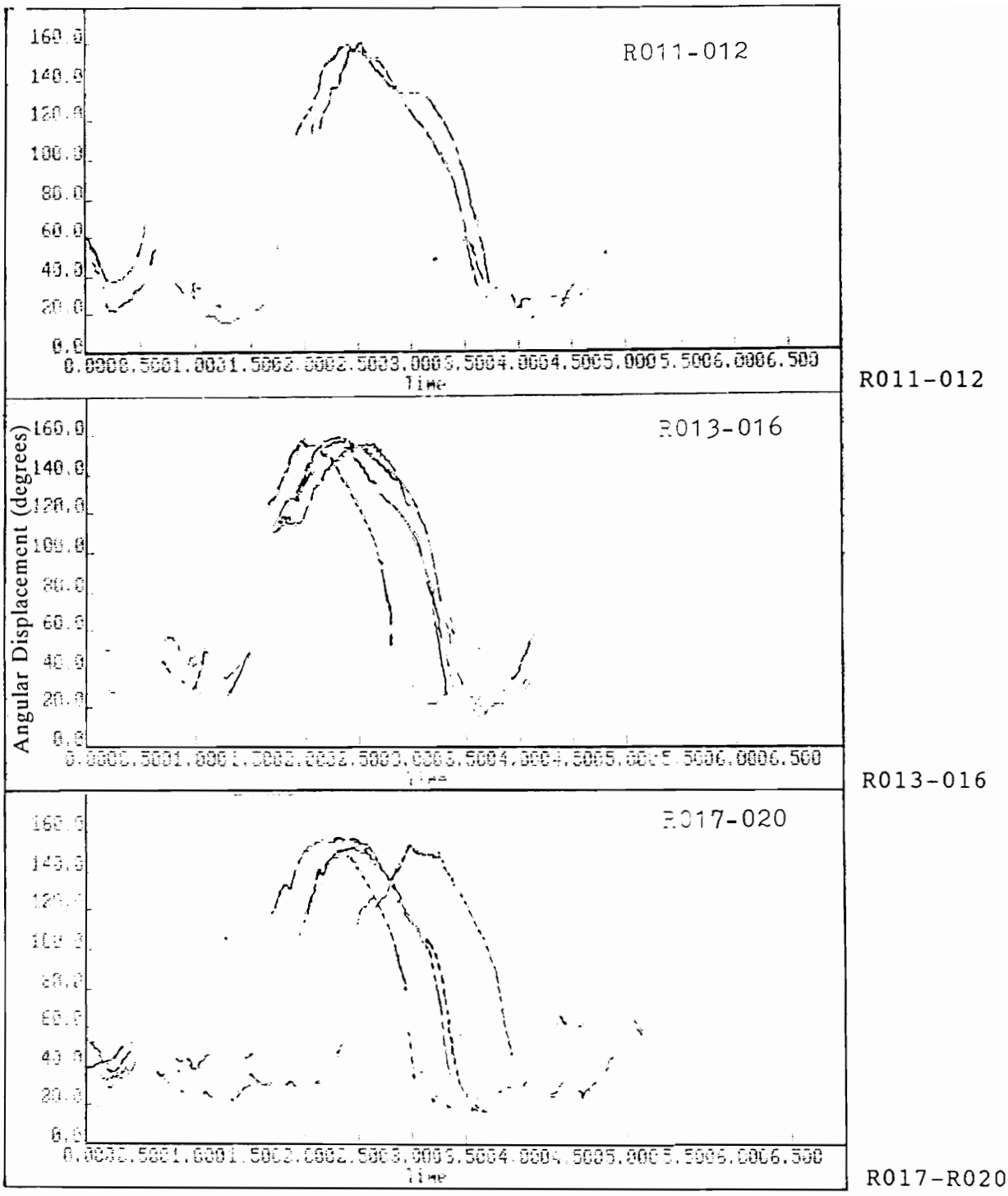

Figure H-2b. Right Shoulder

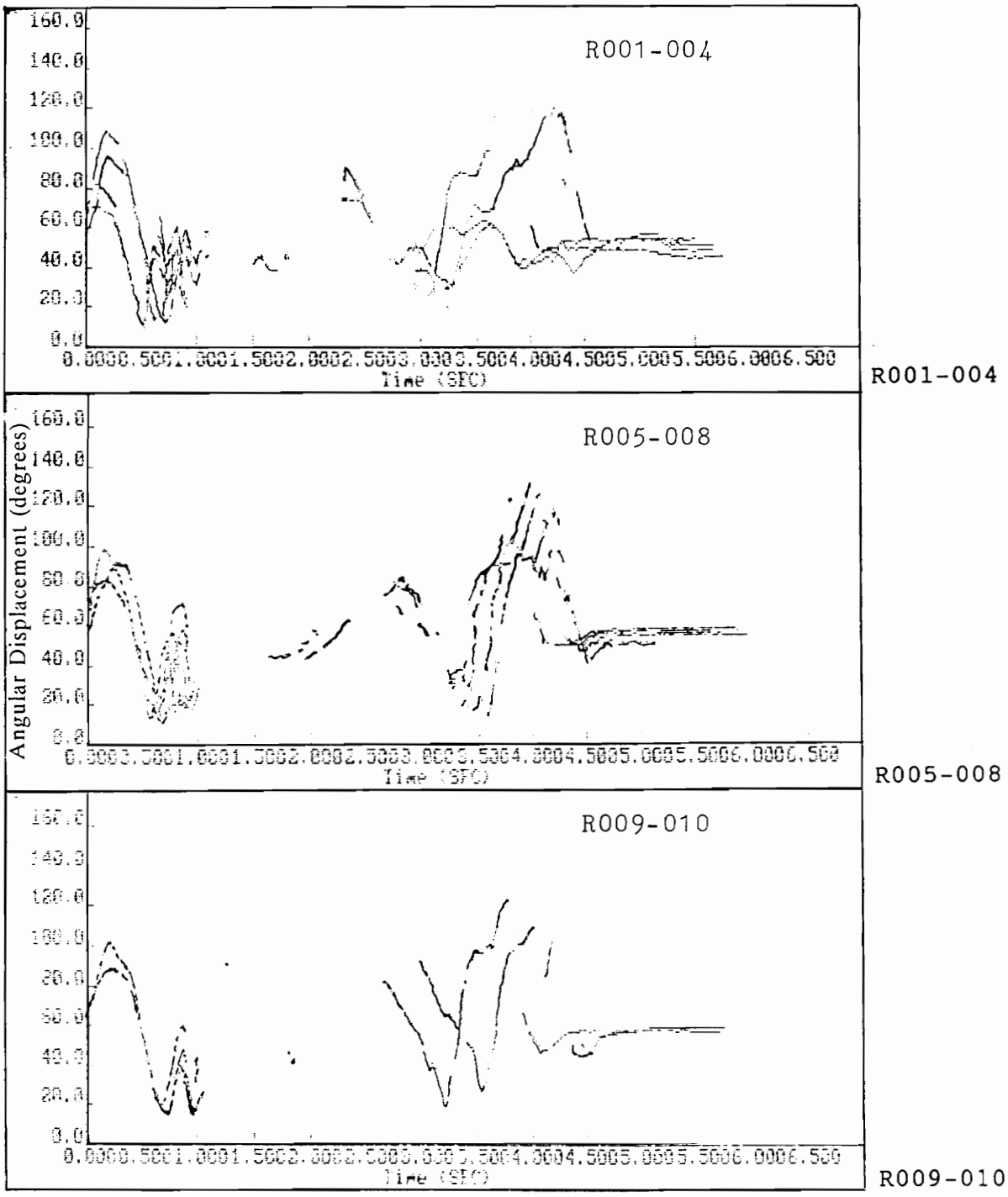

Figure H-3a. Left Elbow

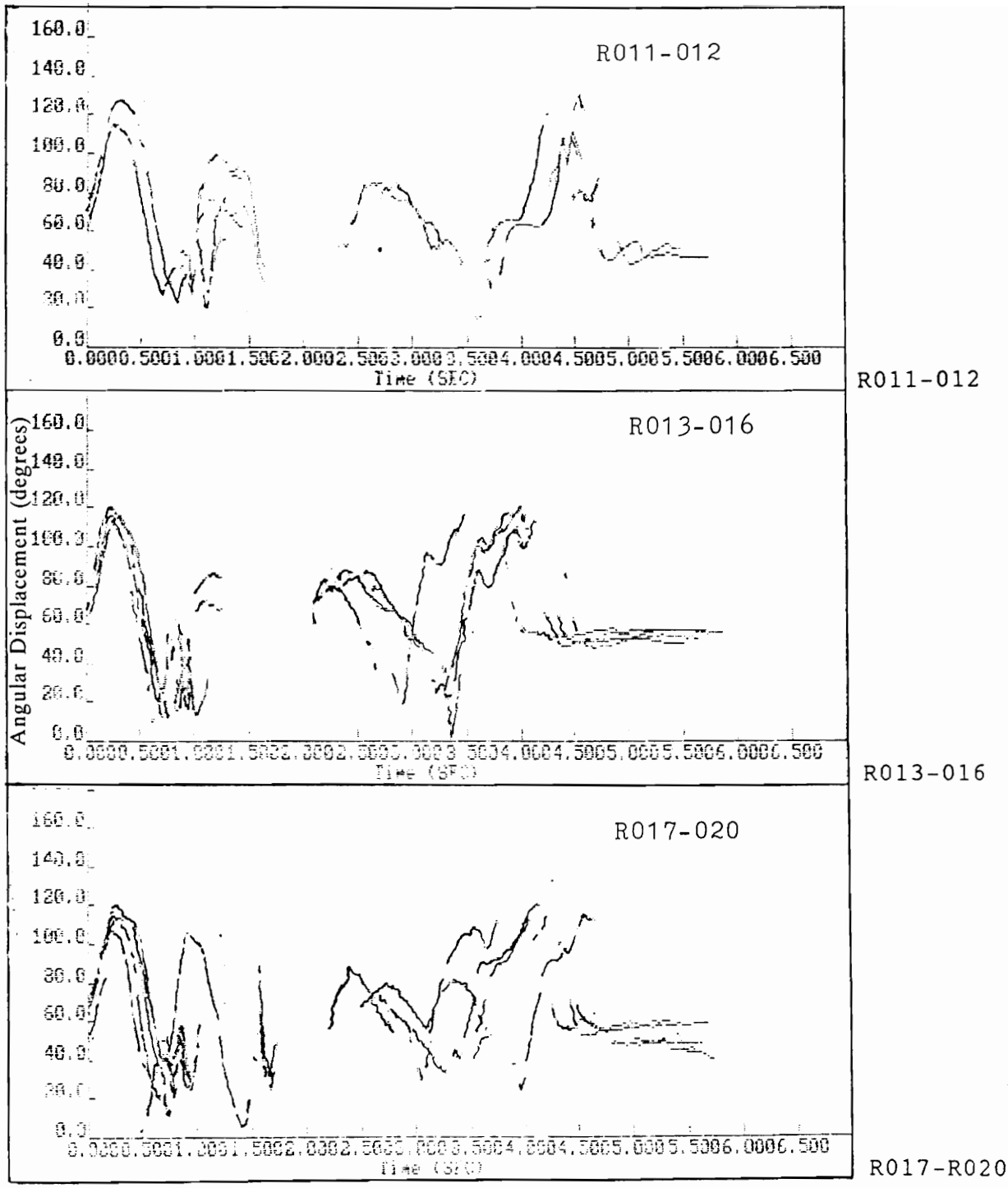

Figure H-3b. Left Elbow

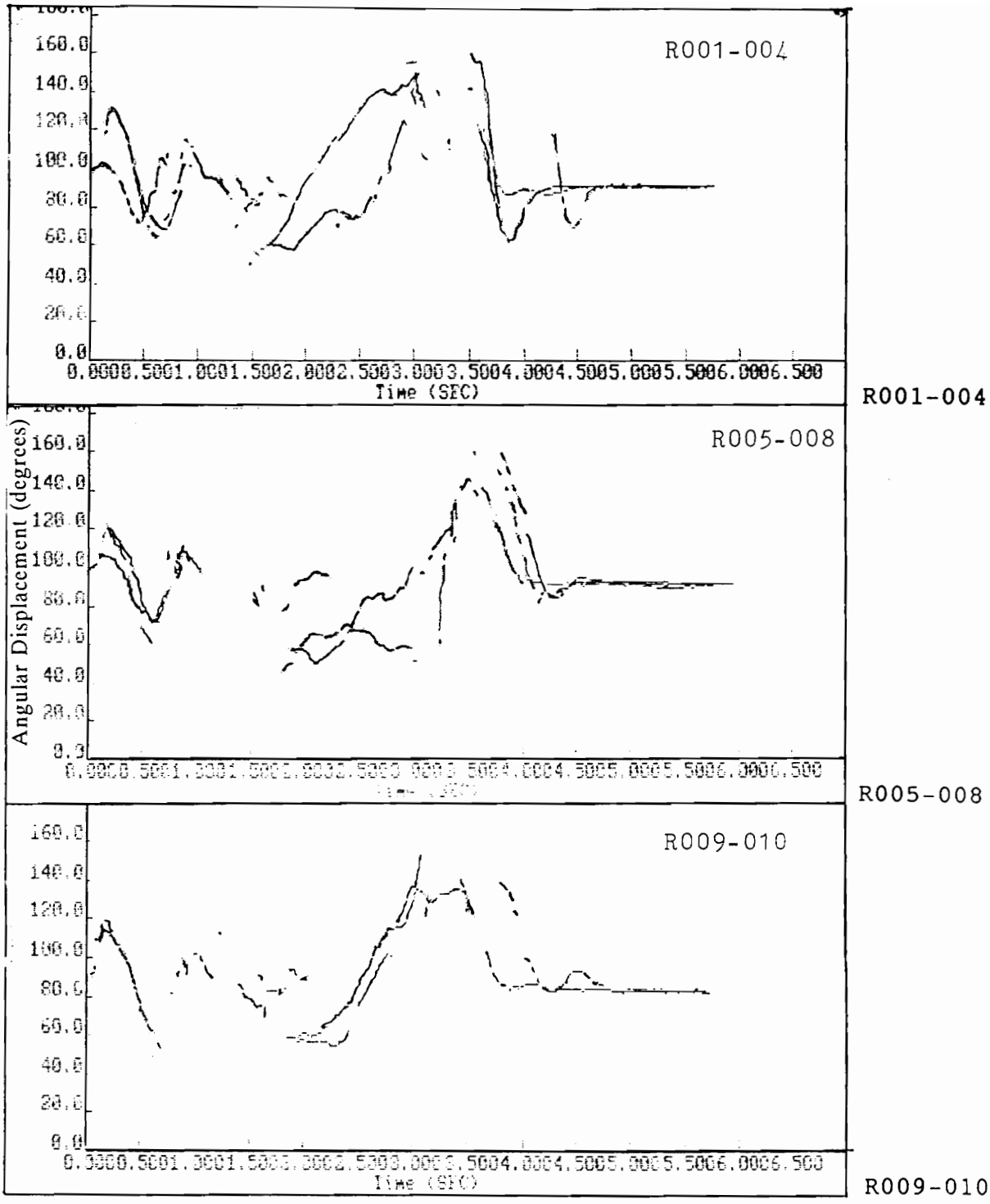

Figure H4a. Right Elbow

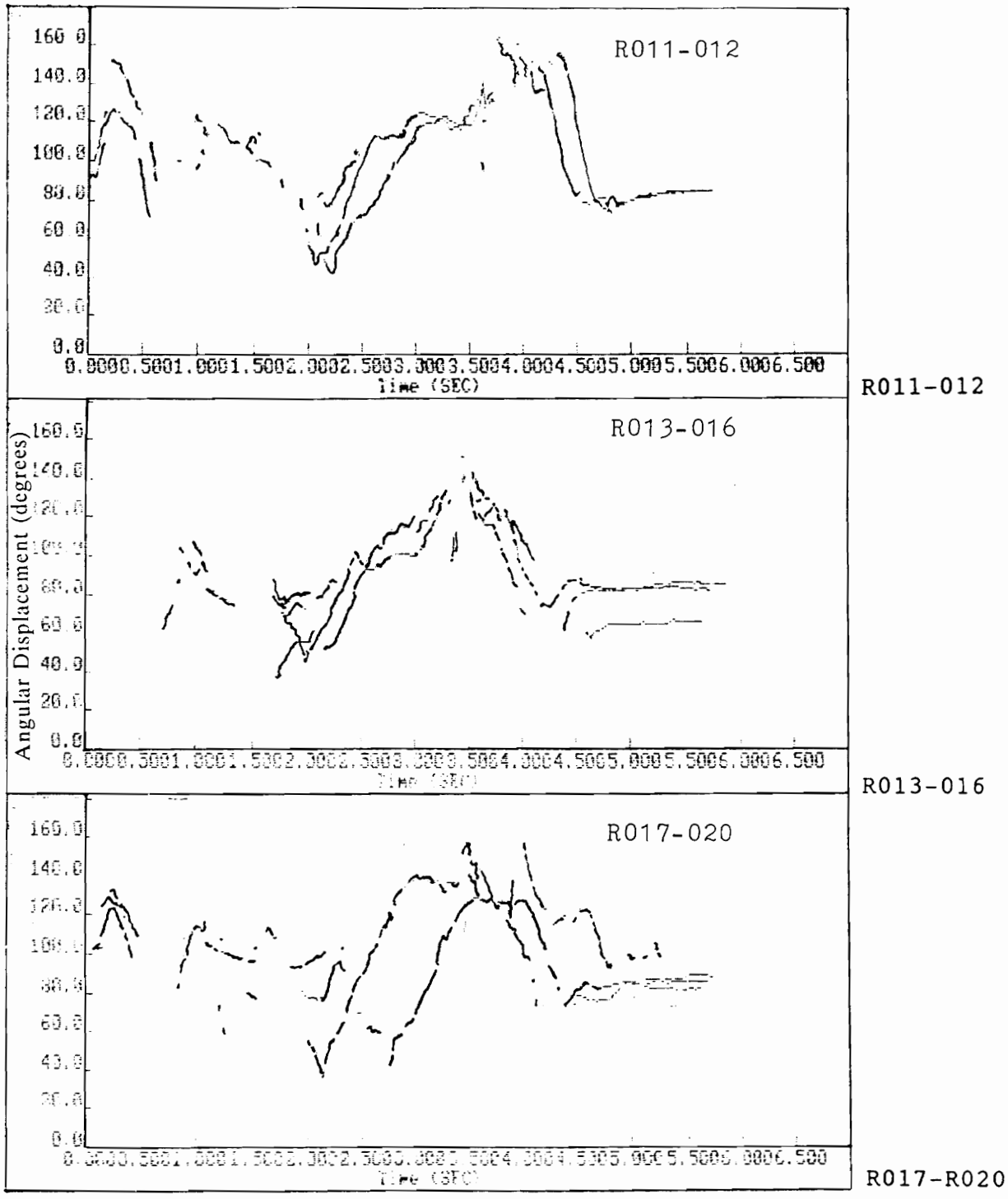

Figure H4b. Right Elbow

APPENDIX I
INTRA-TRIAL CONSISTENCY GRAPHS OF WATSMART DATA

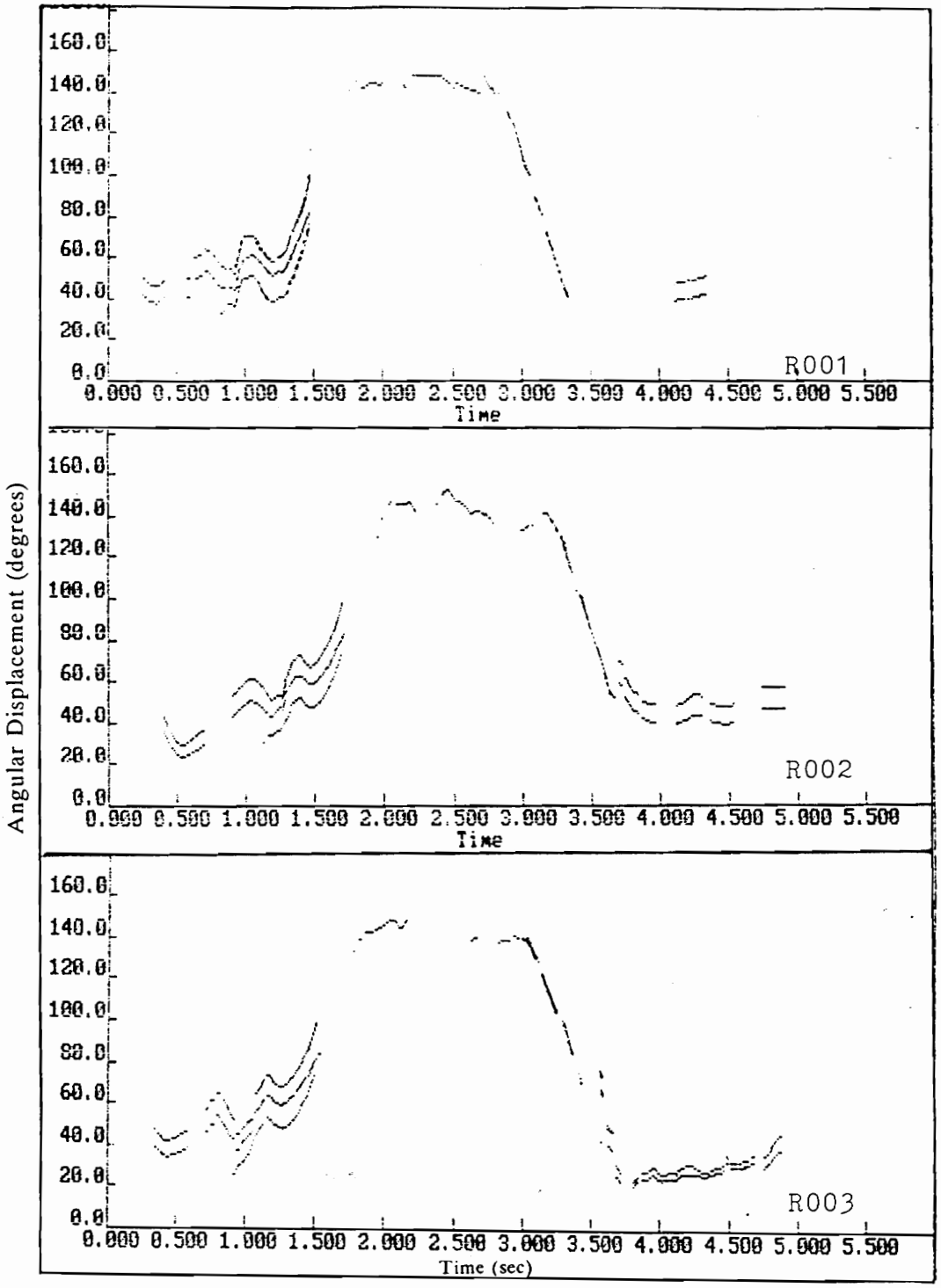

Figure I1a. Left Shoulder

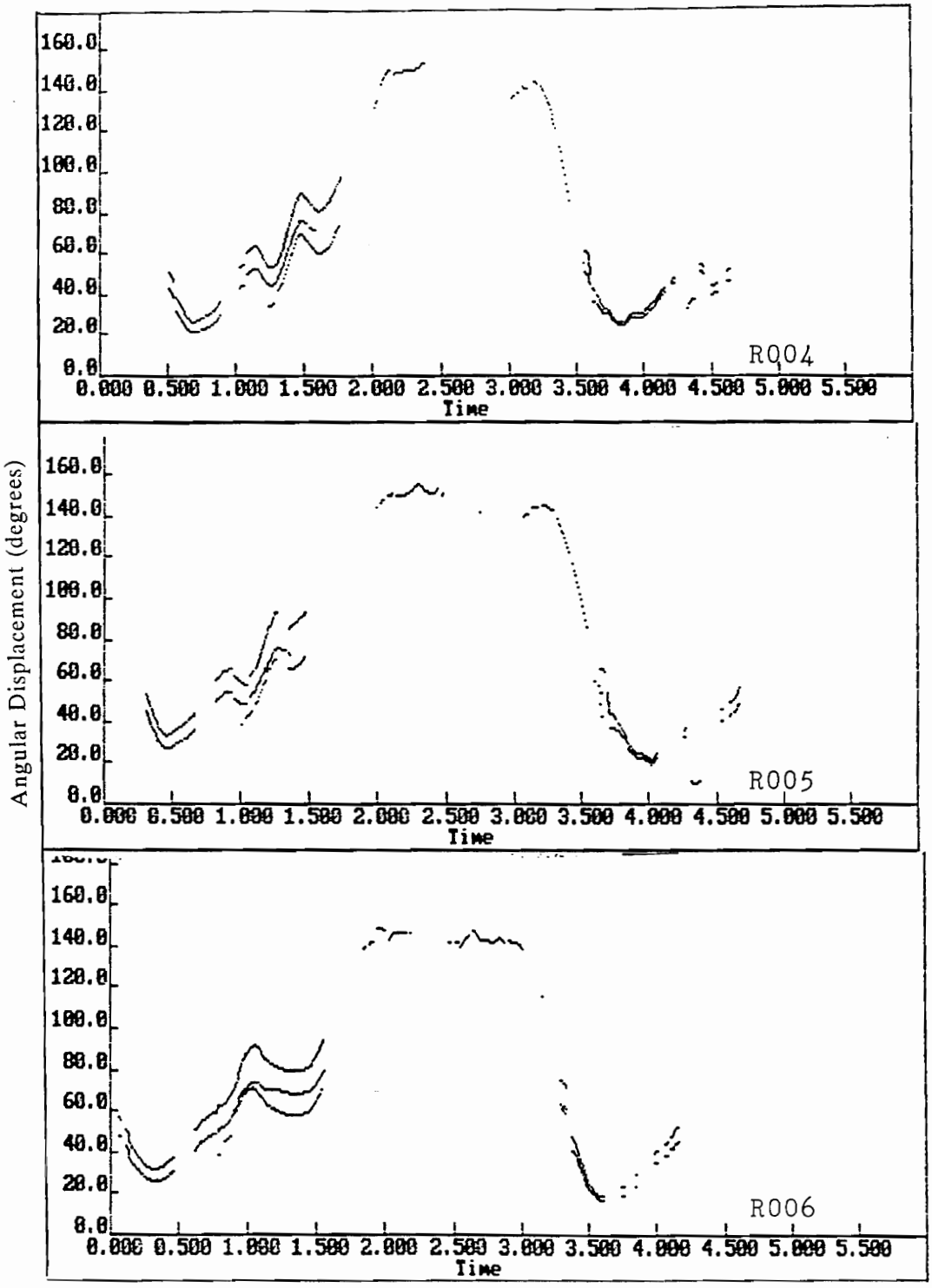

Figure I1b. Left Shoulder

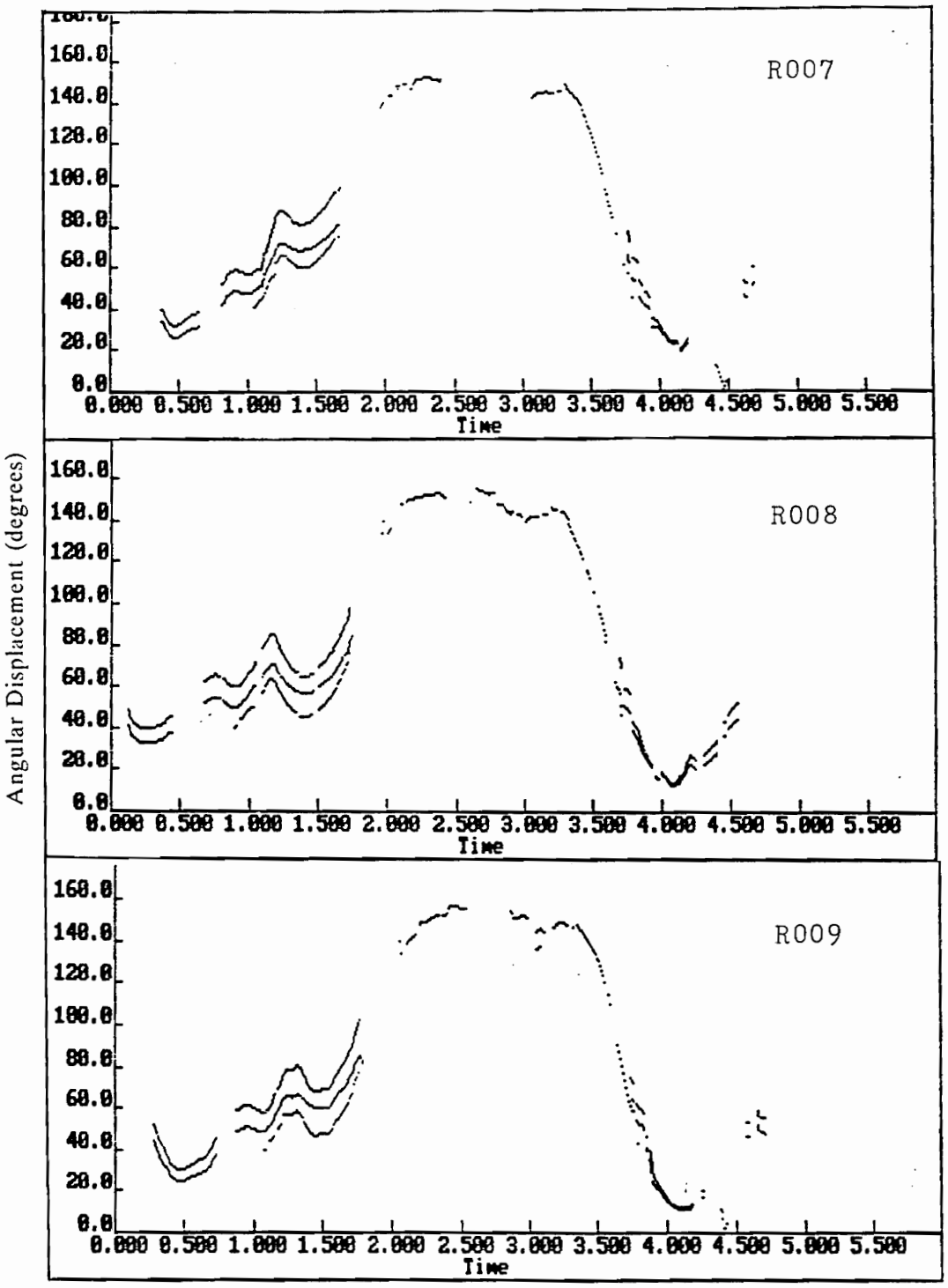

Figure I1c. Left Shoulder

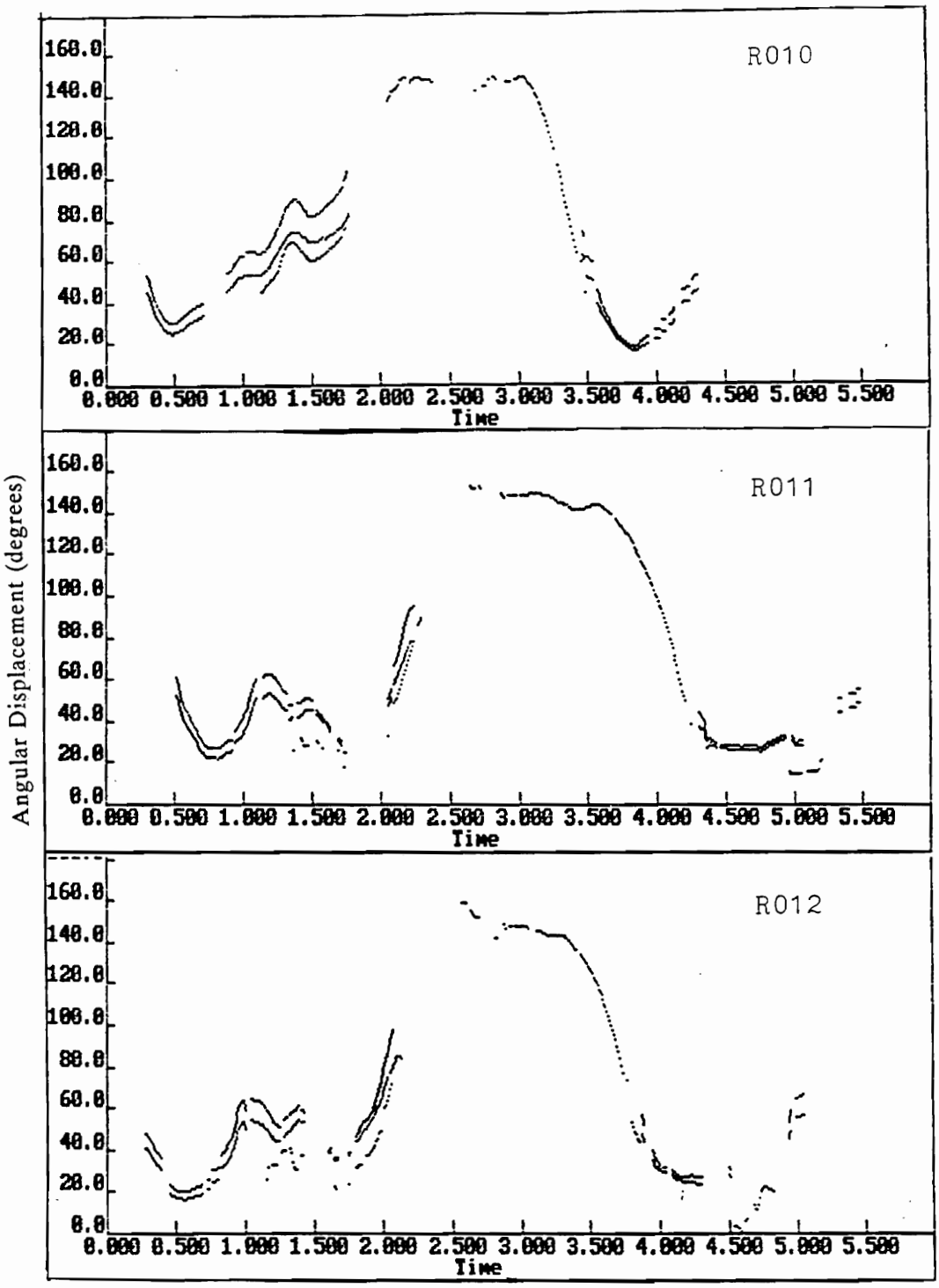

Figure I1d. Left Shoulder

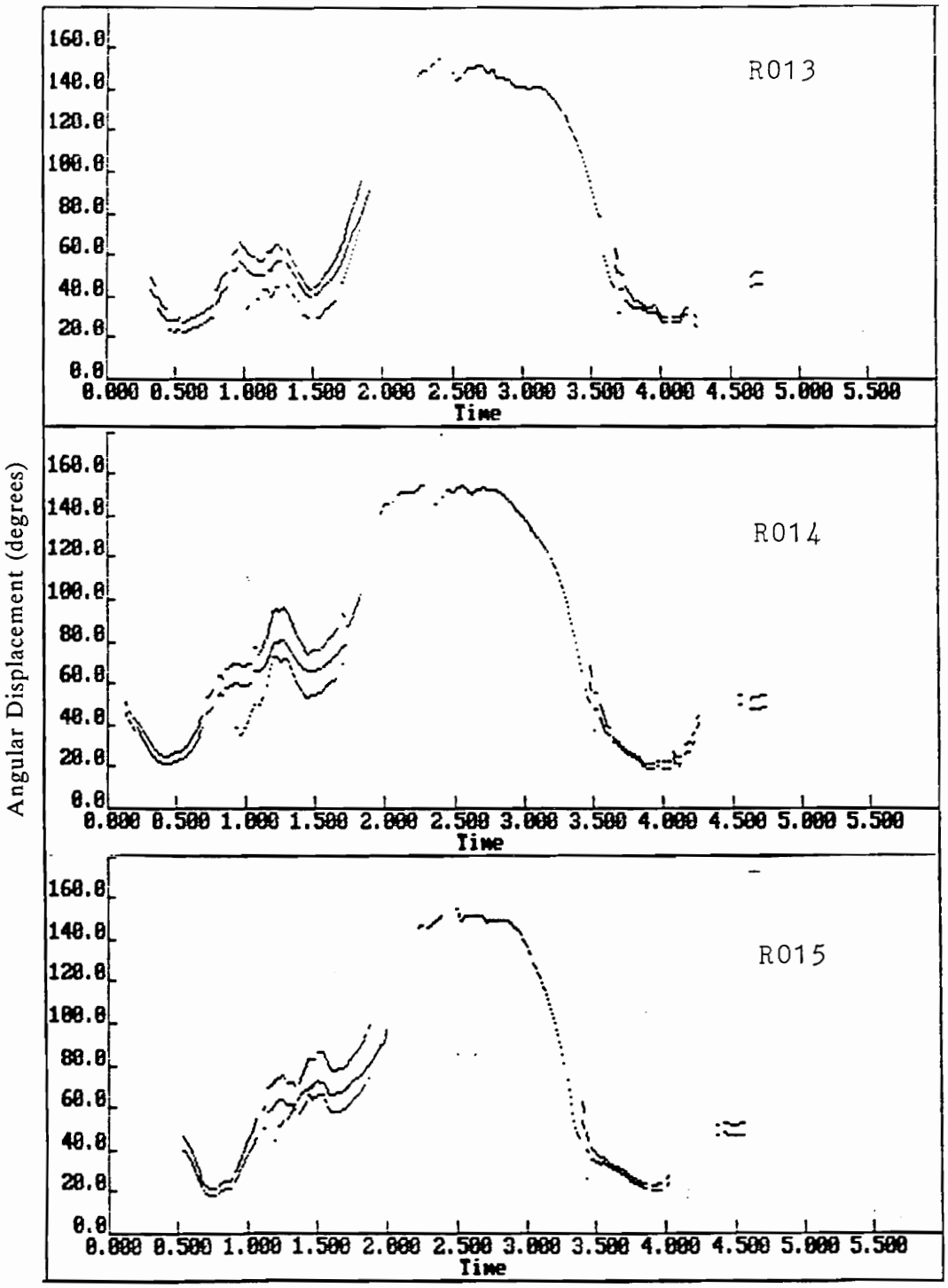

Figure I1e. Left Shoulder

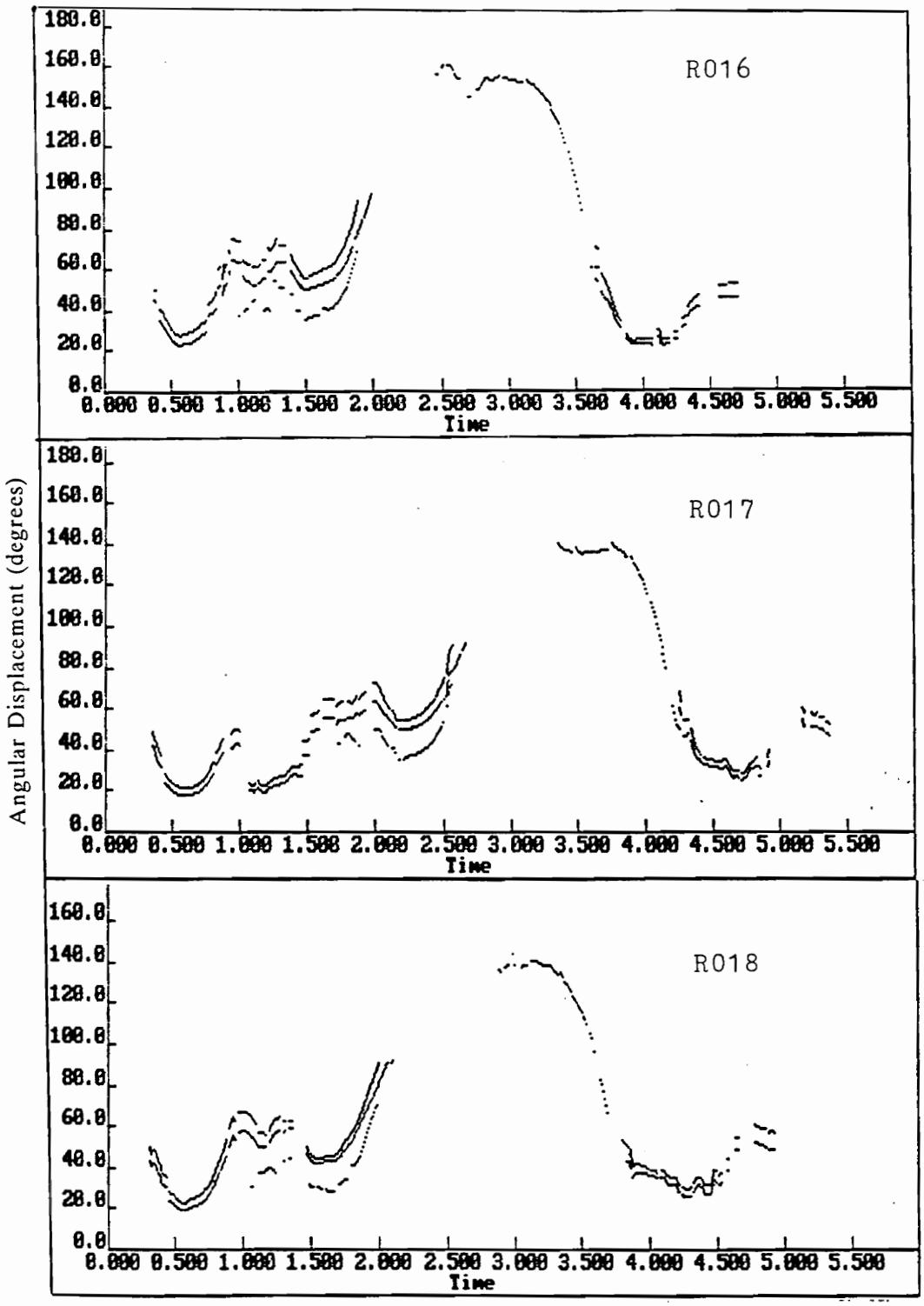

Figure I1f. Left Shoulder

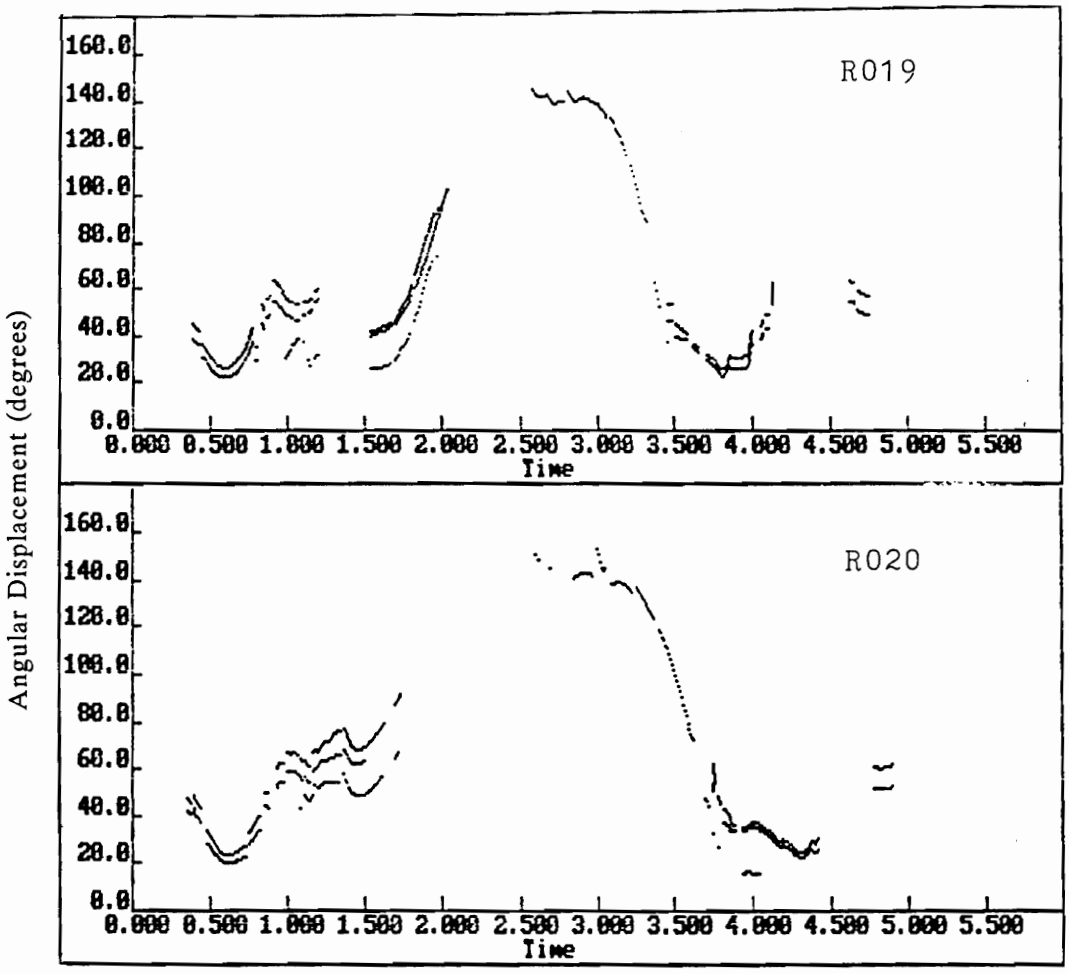

Figure I1g. Left Shoulder

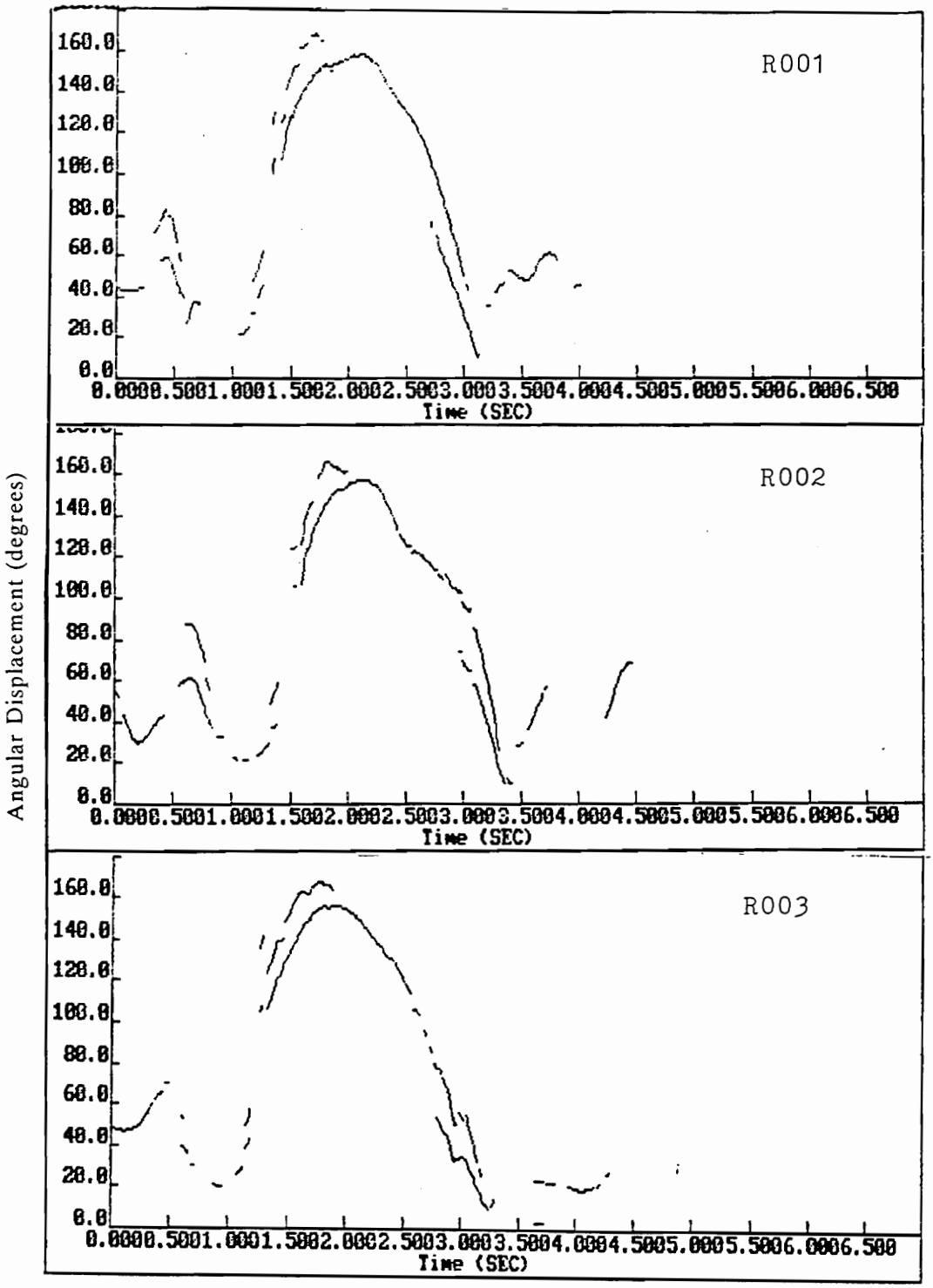

Figure I2a. Right Shoulder

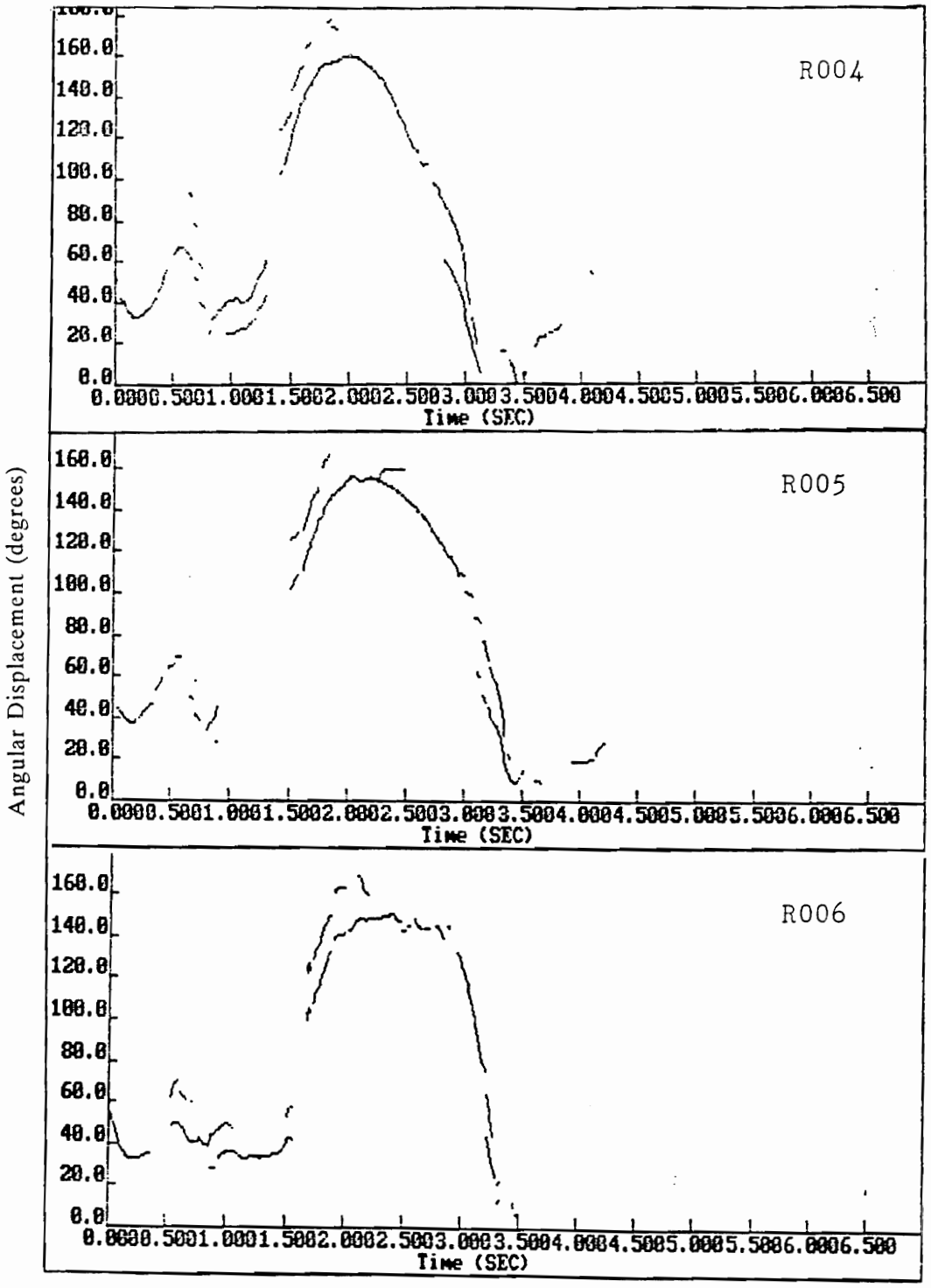

Figure I2b. Right Shoulder

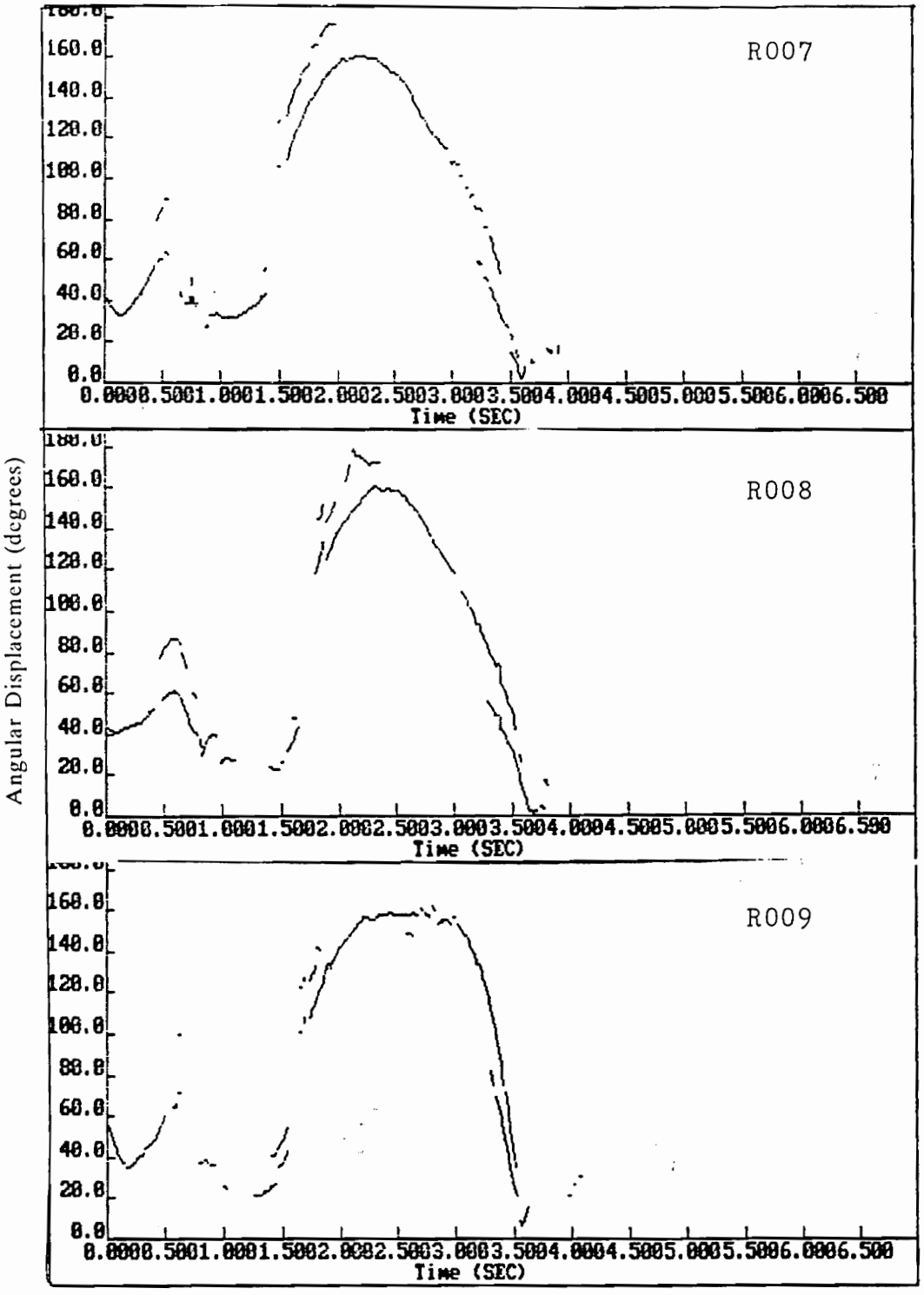

Figure I2c. Right Shoulder

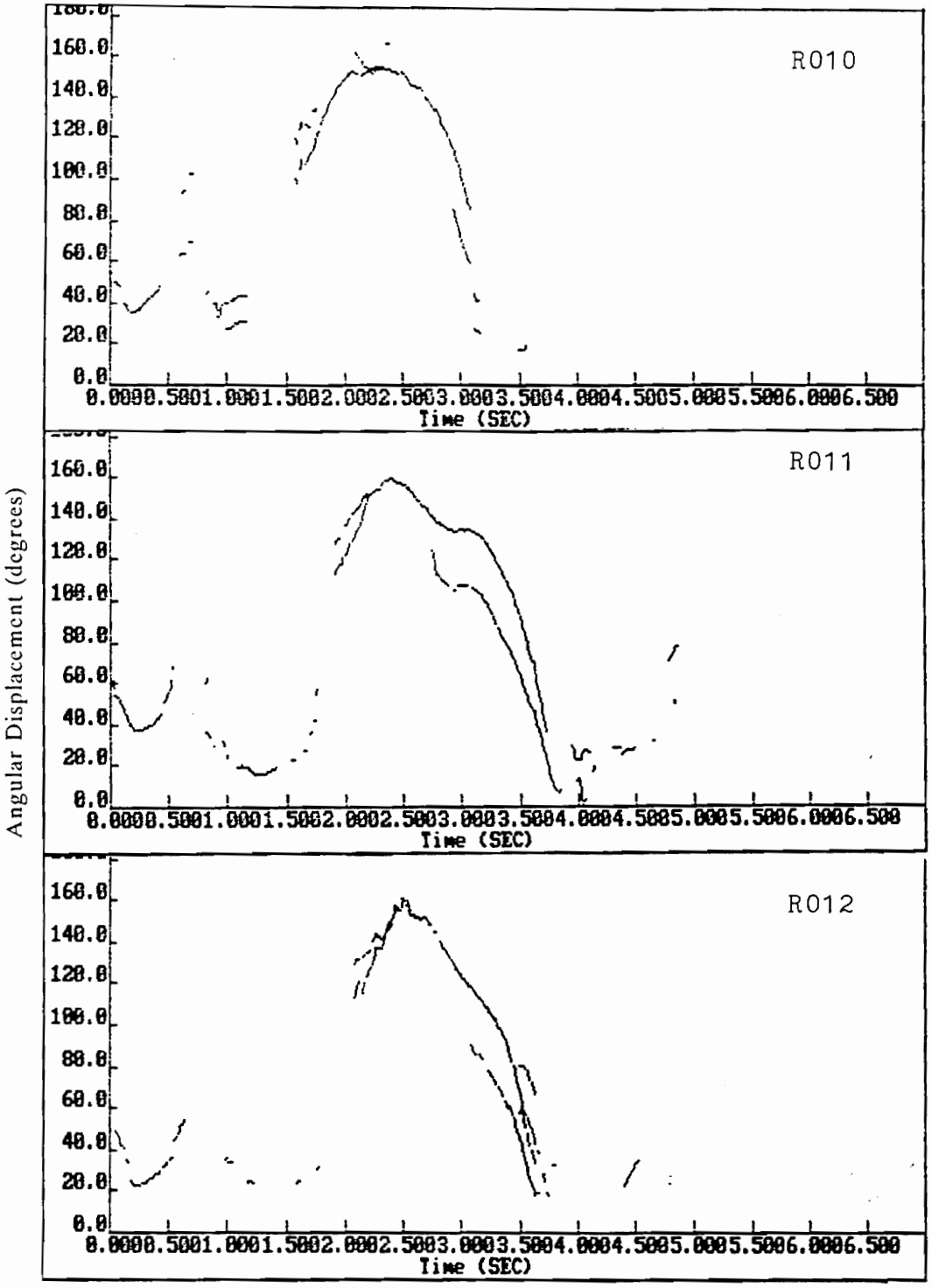

Figure I2d. Right Shoulder

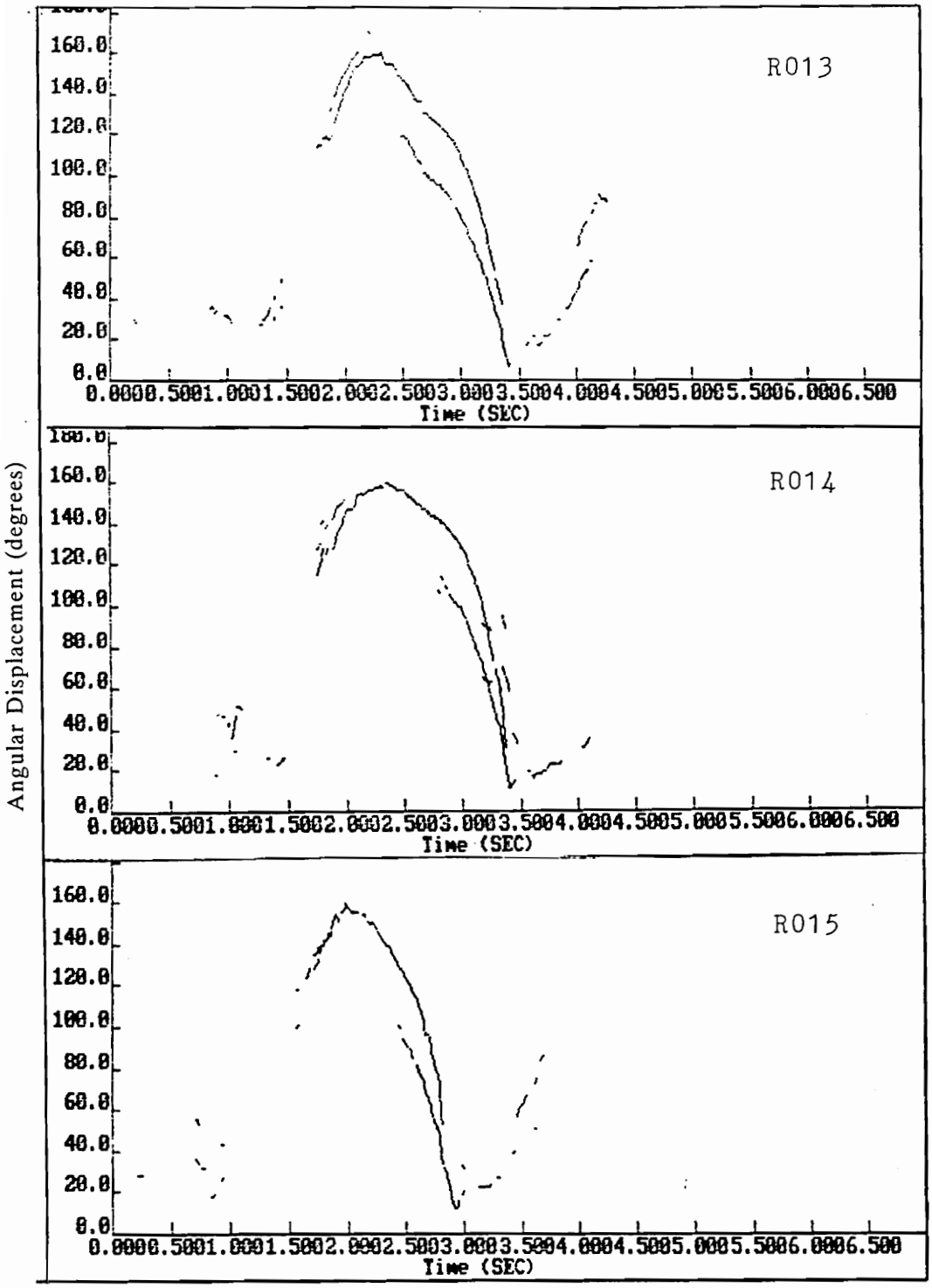

Figure I2e. Right Shoulder

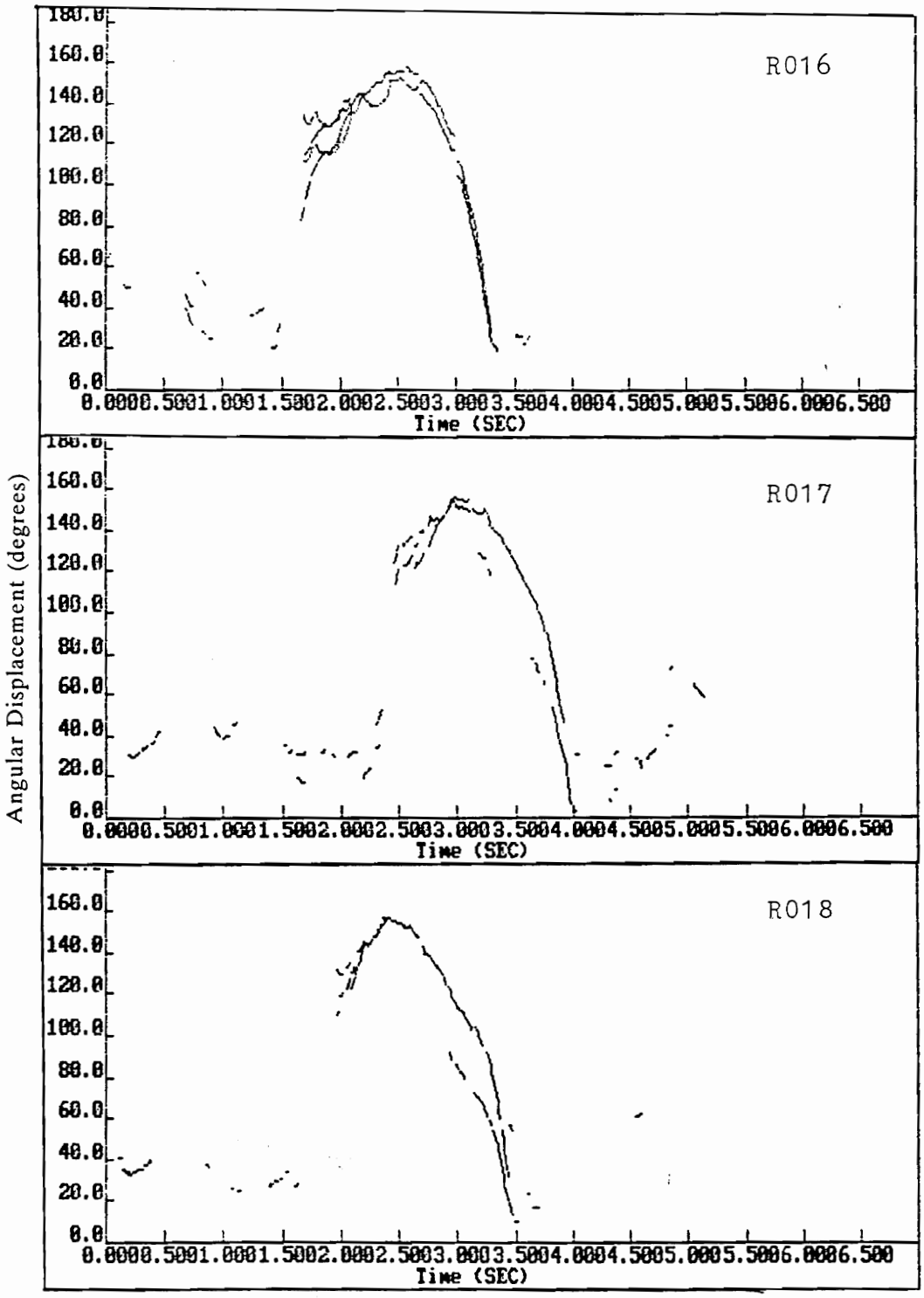

Figure I2f. Right Shoulder

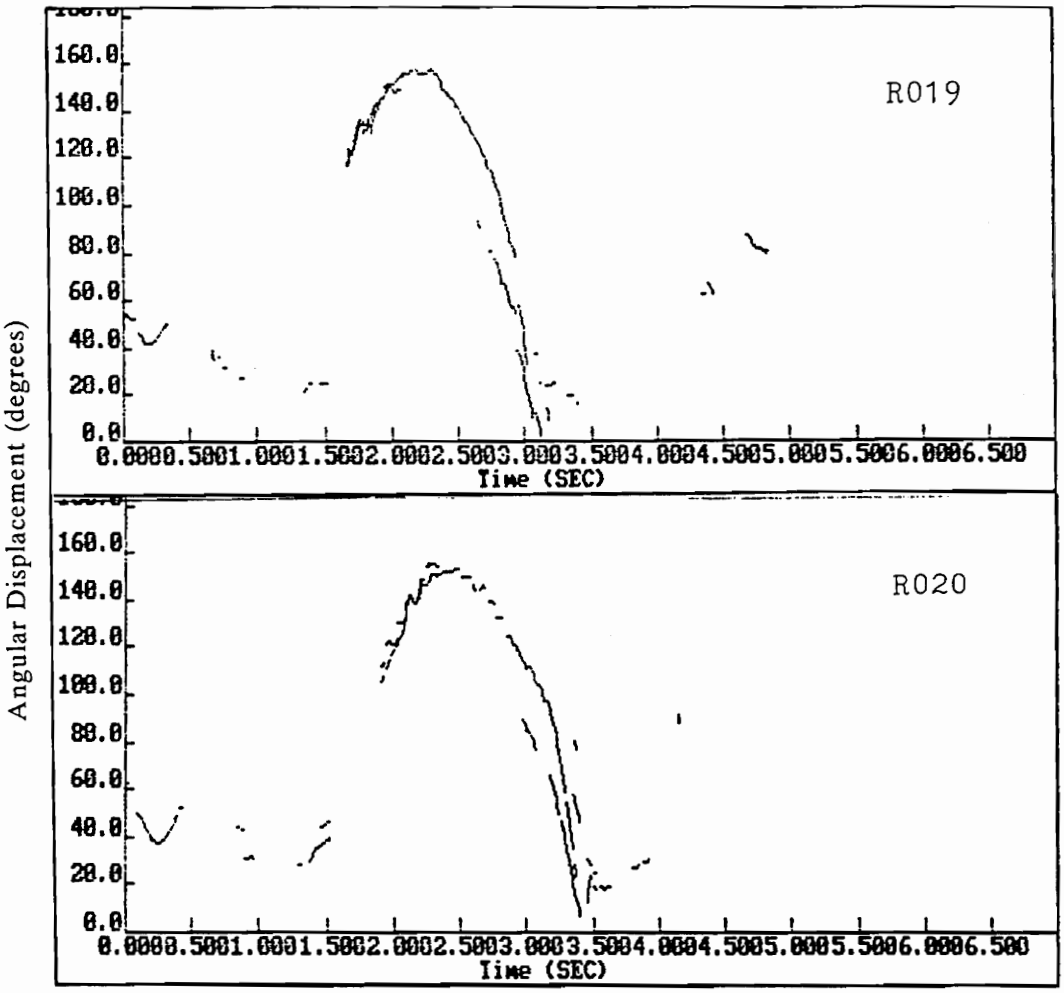

Figure I2g. Right Shoulder

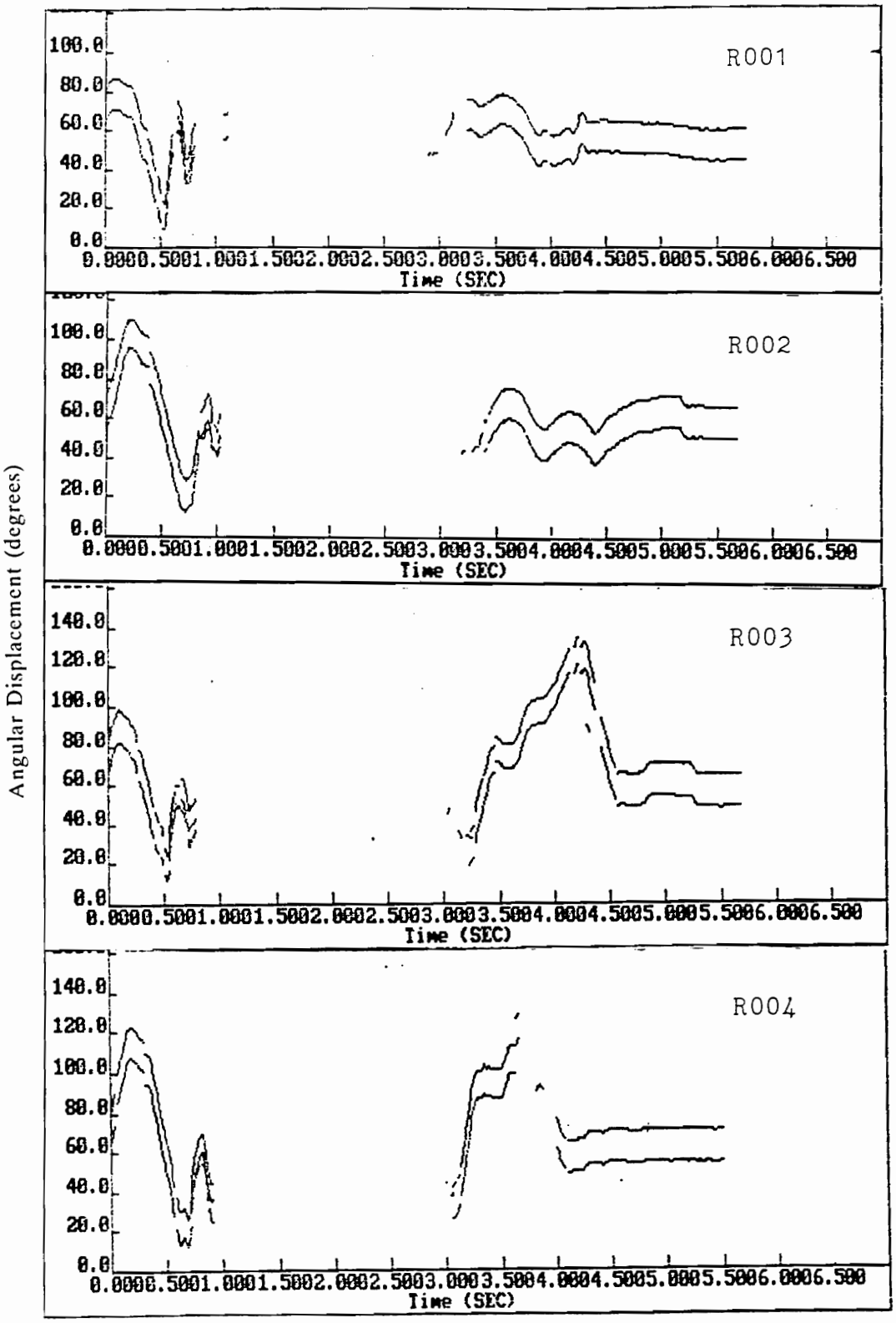

Figure I3a. Left Elbow

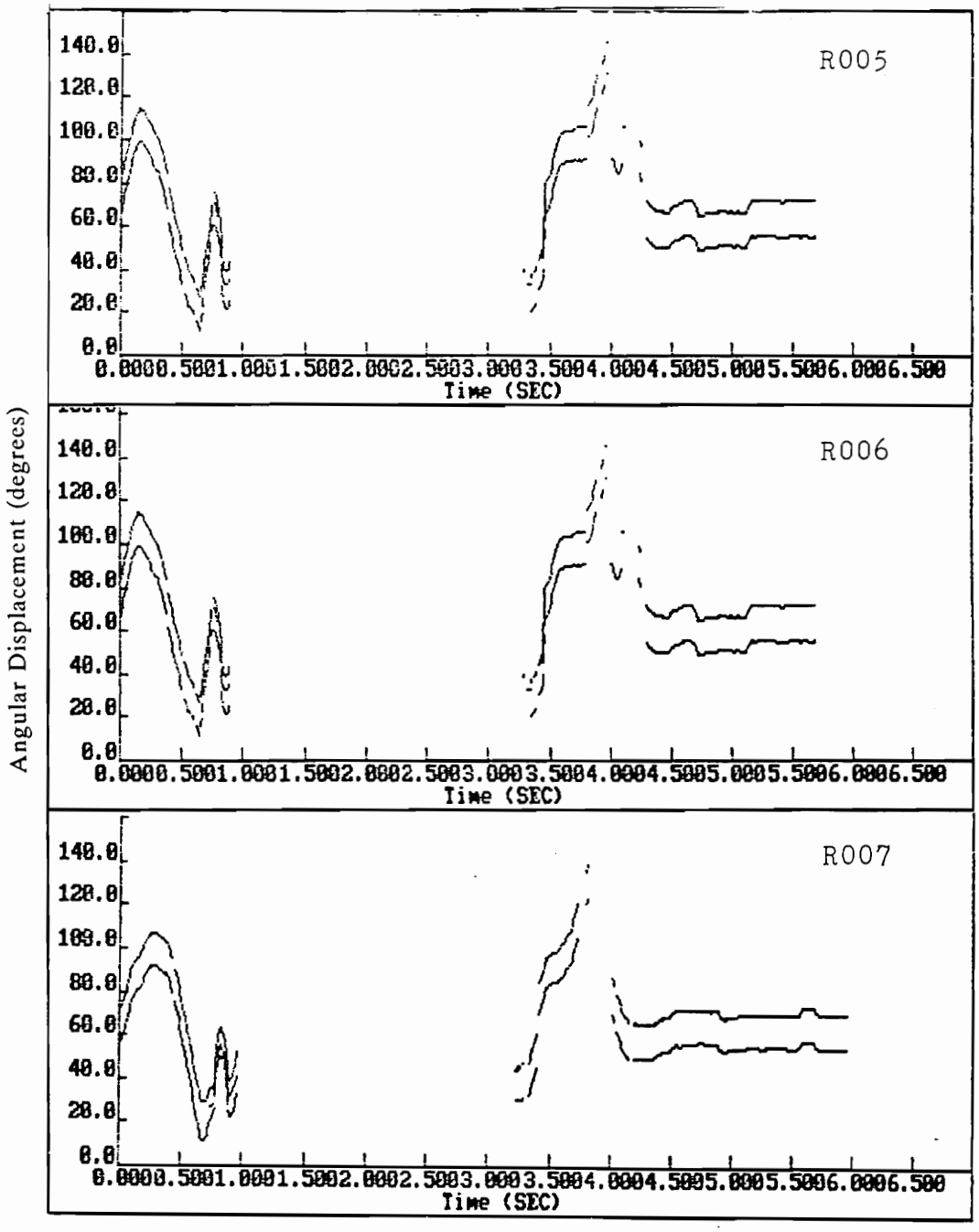

Figure I3b. Left Elbow

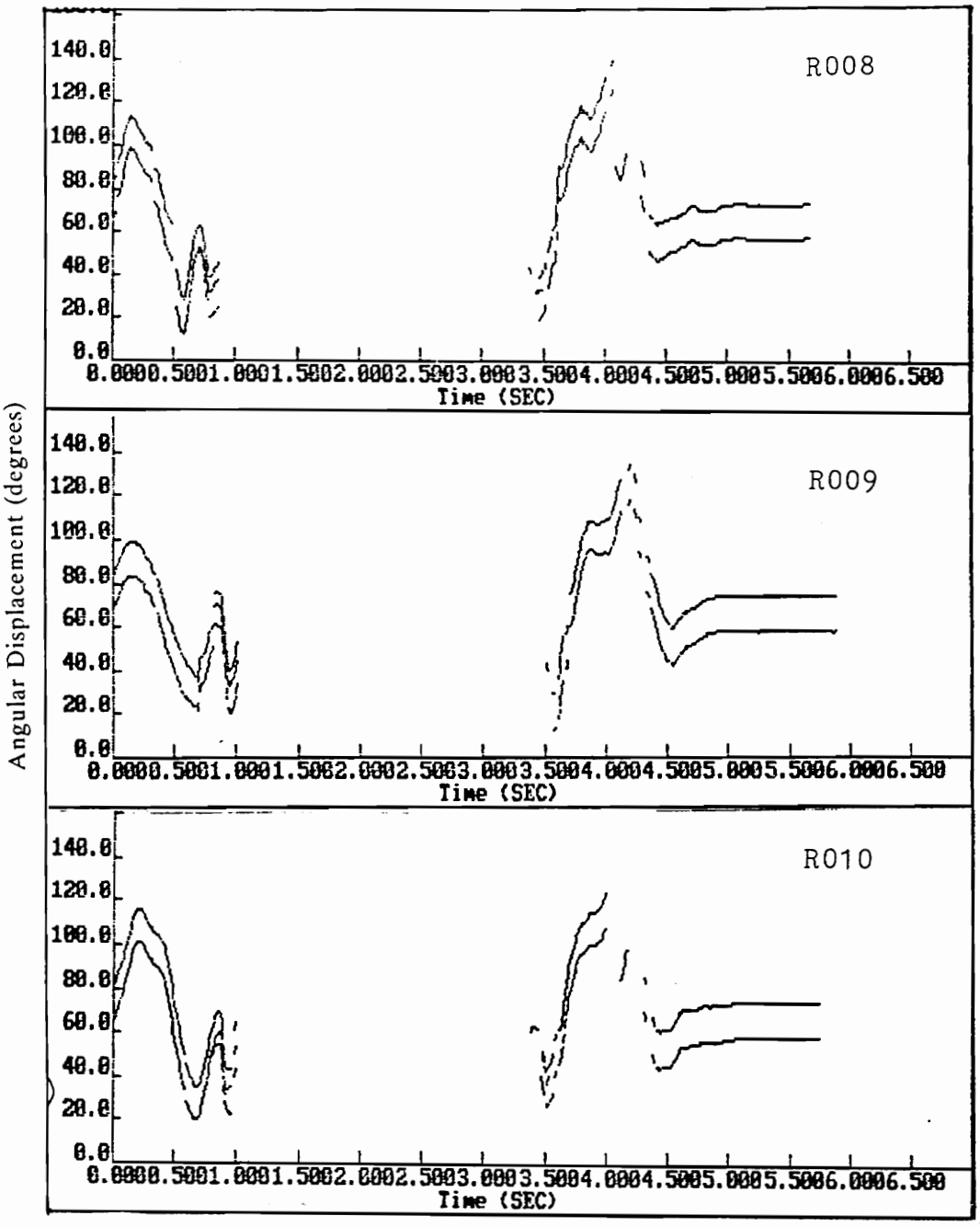

Figure I3c. Left Elbow

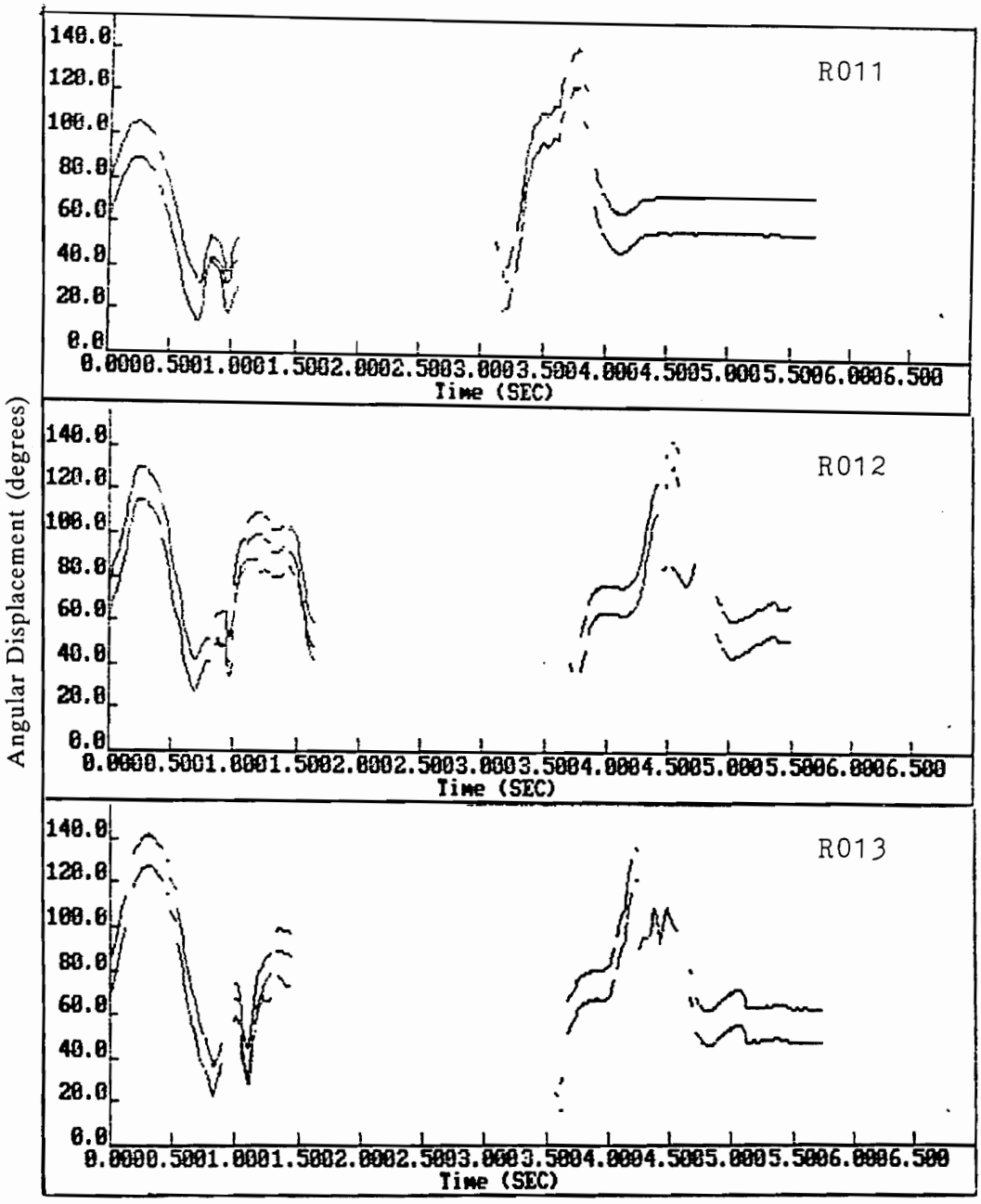

Figure I3d. Left Elbow

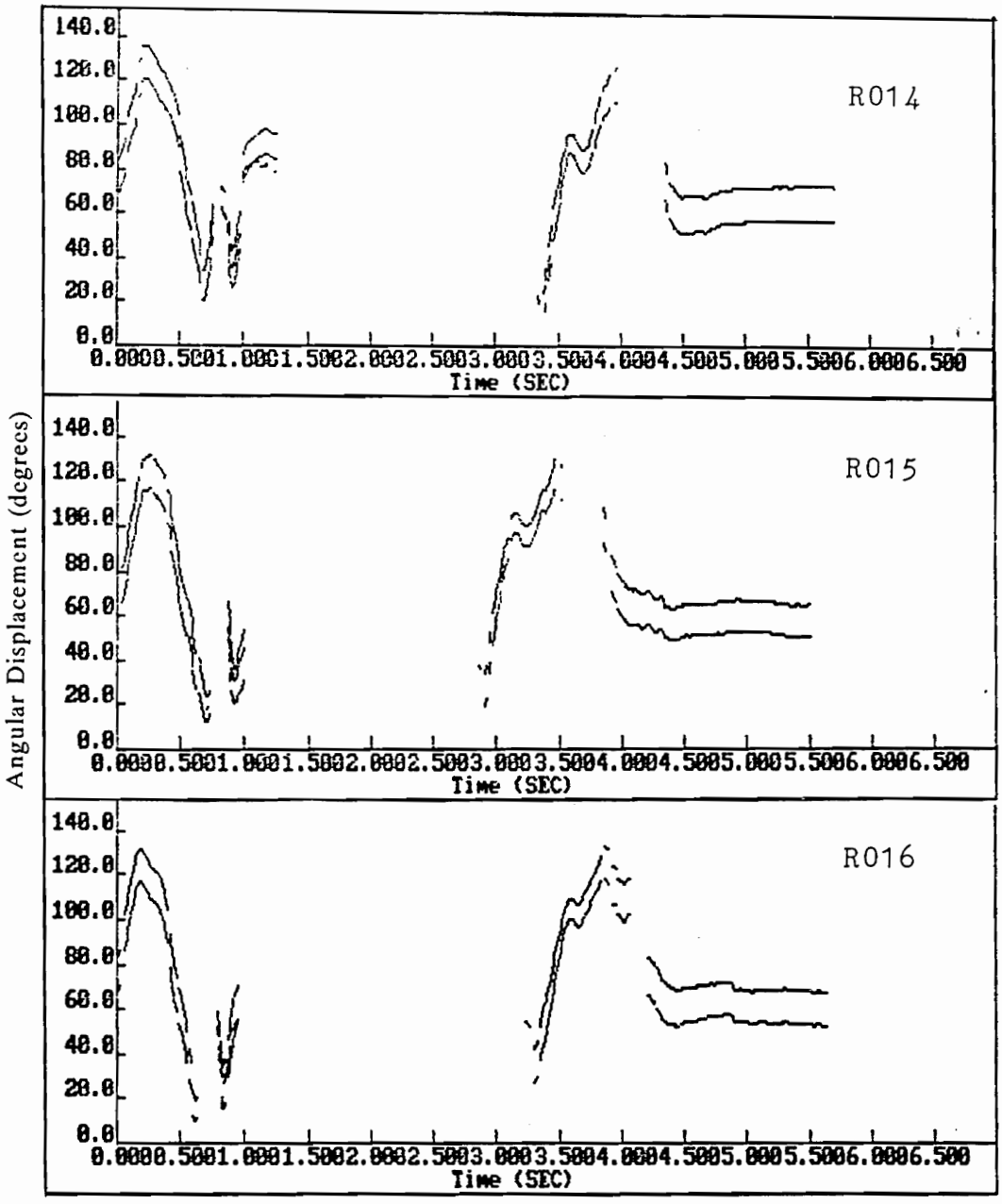

Figure I3e. Left Elbow

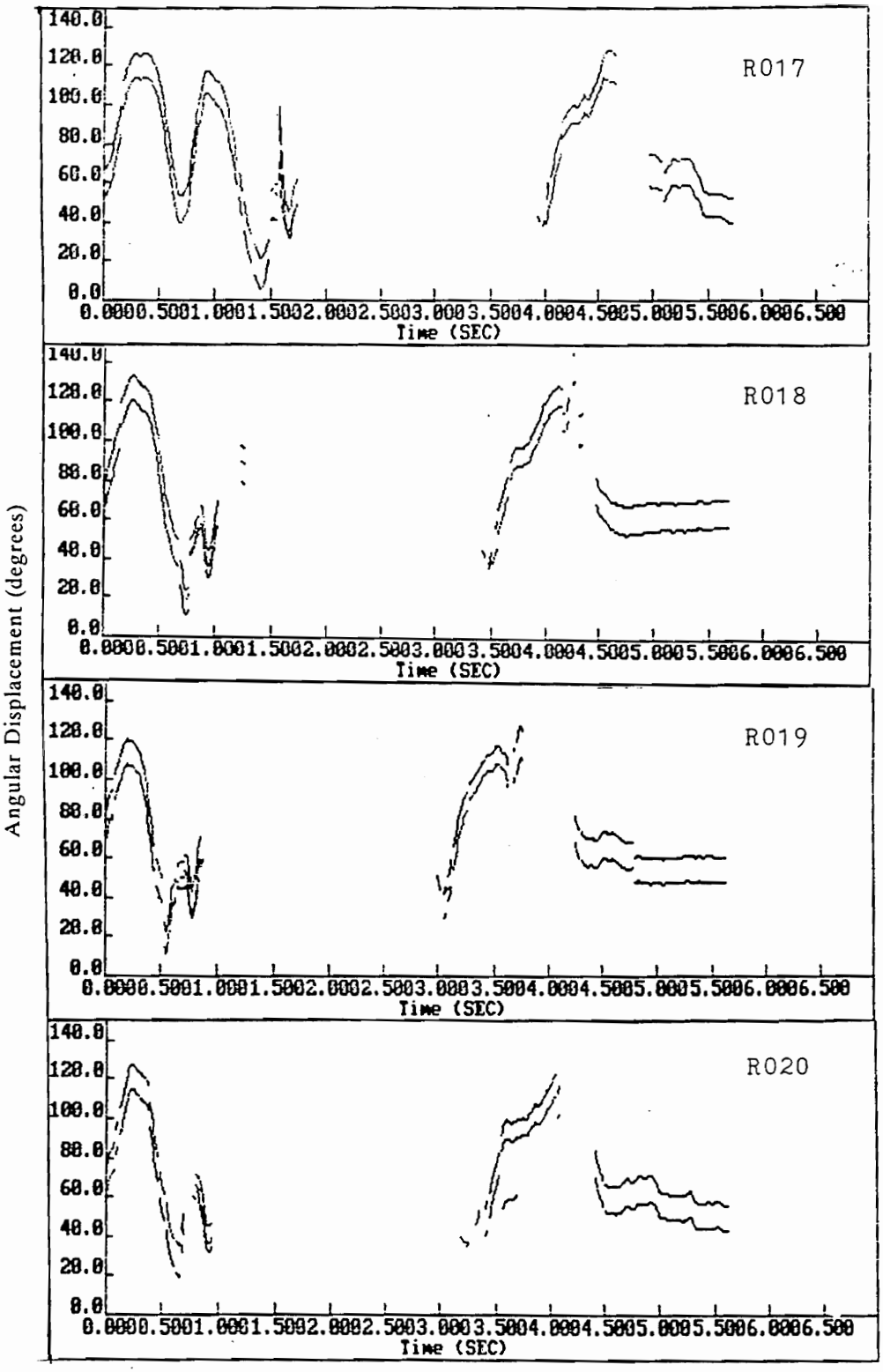

Figure I3f. Left Elbow

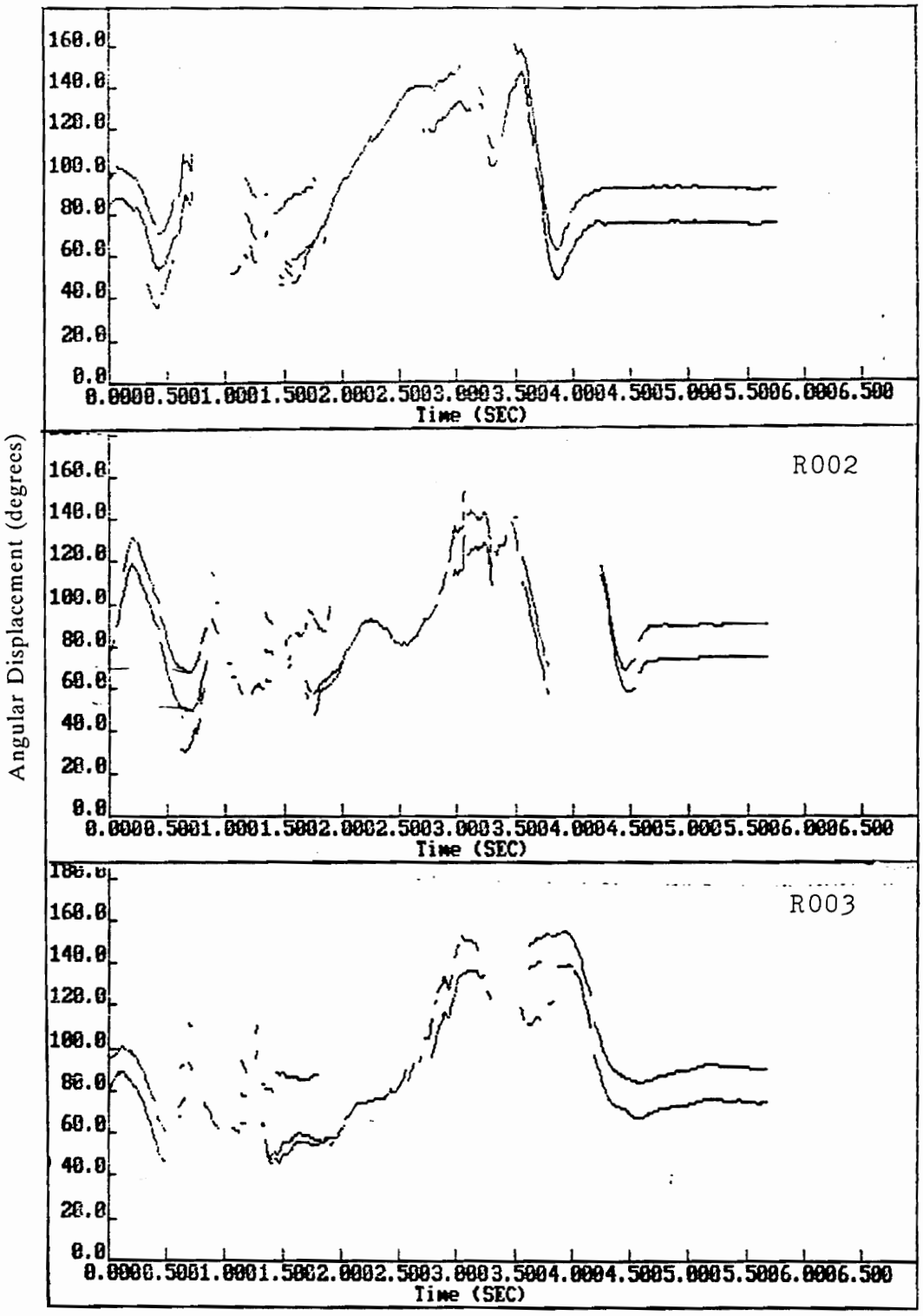

Figure I4a. Right Elbow

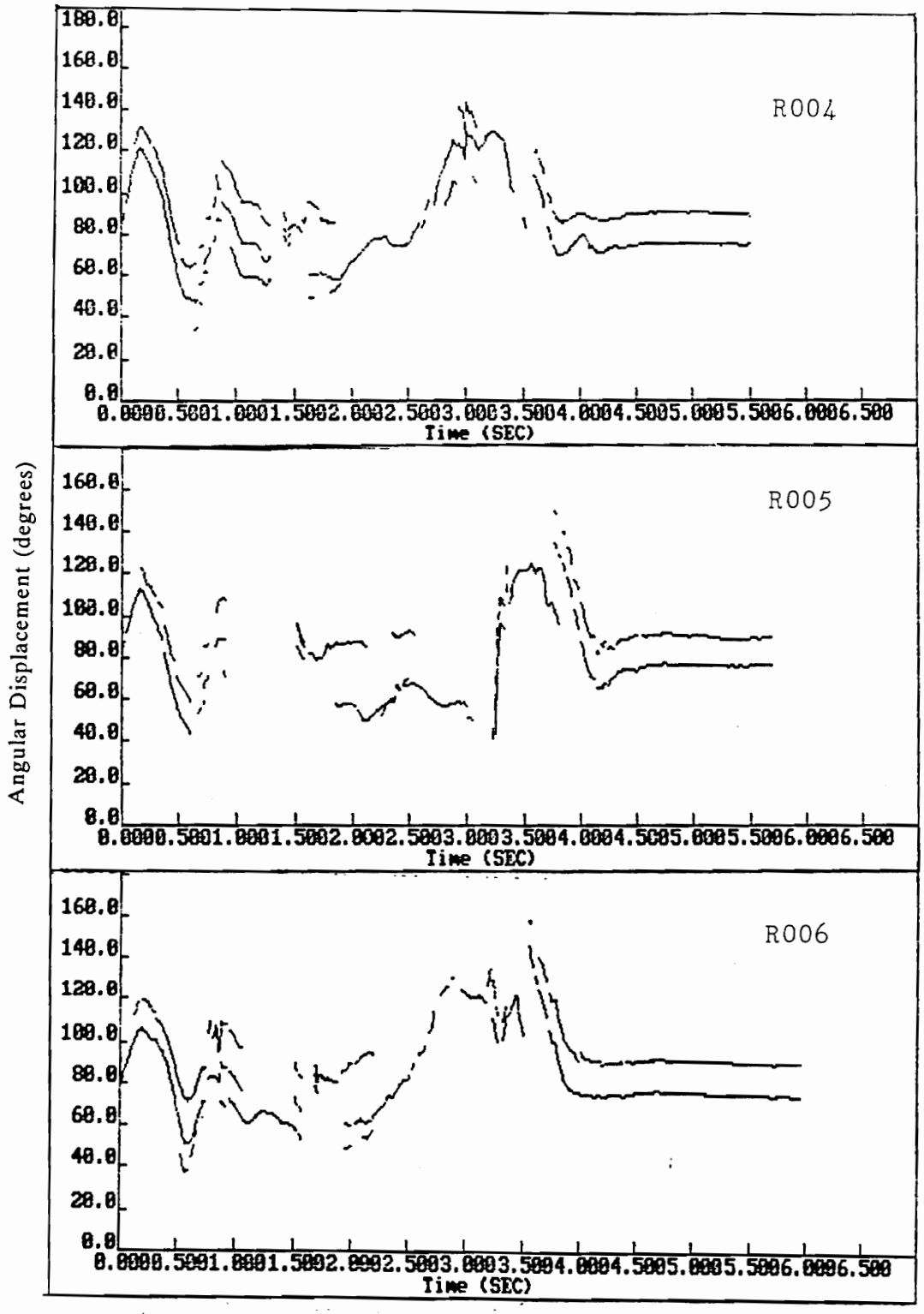

Figure I4b. Right Elbow

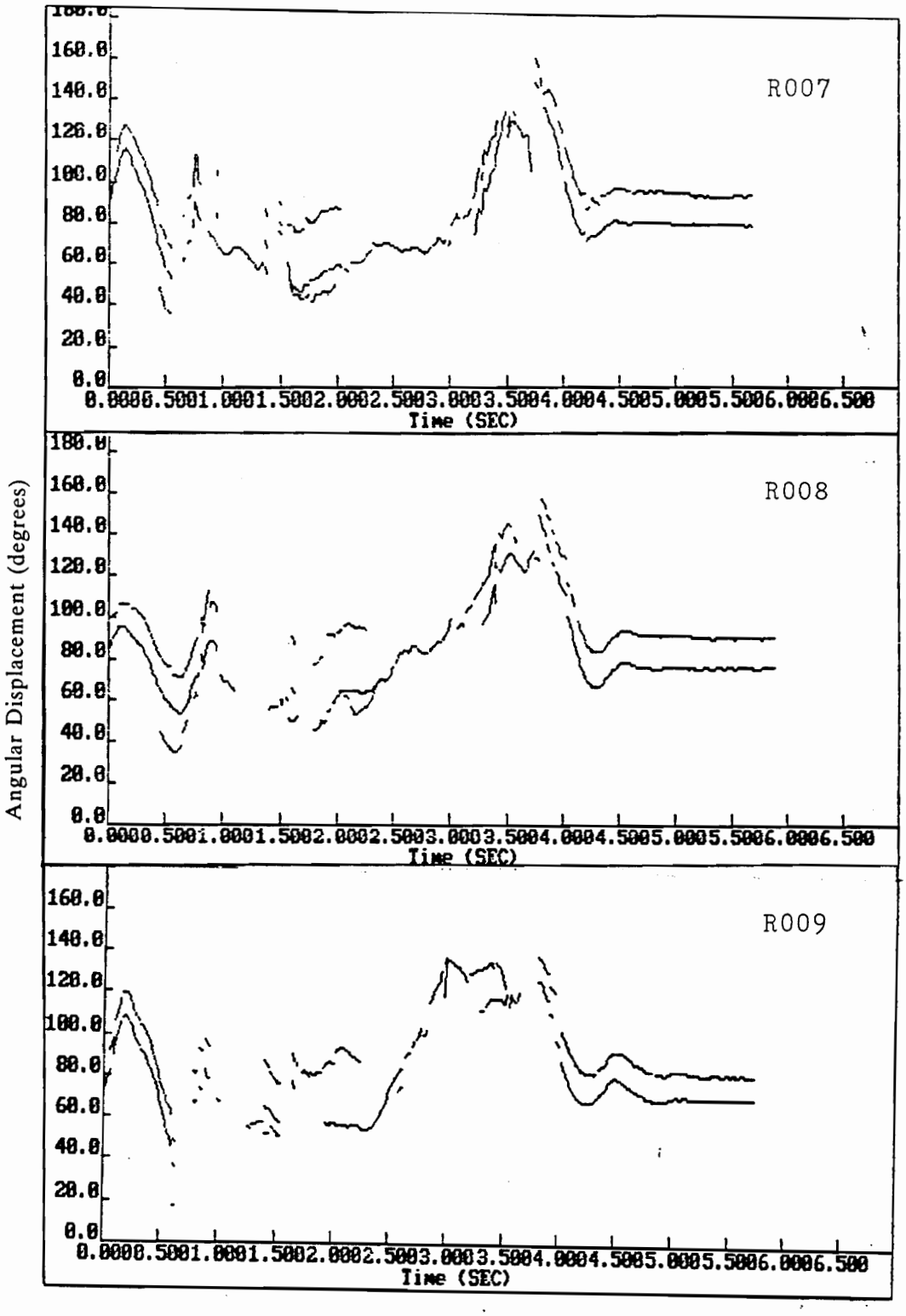

Figure I4c. Right Elbow

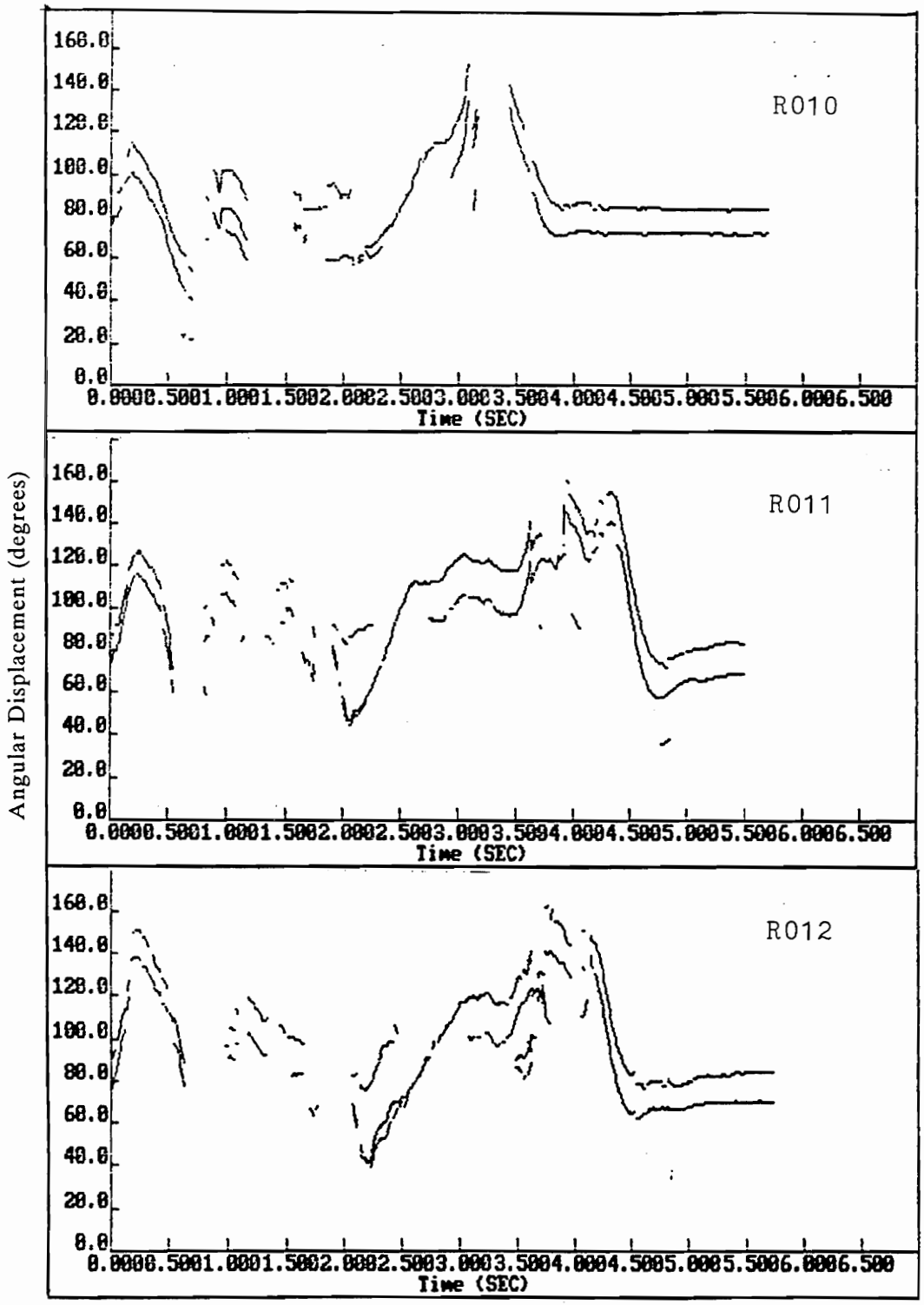

Figure I4d. Right Elbow

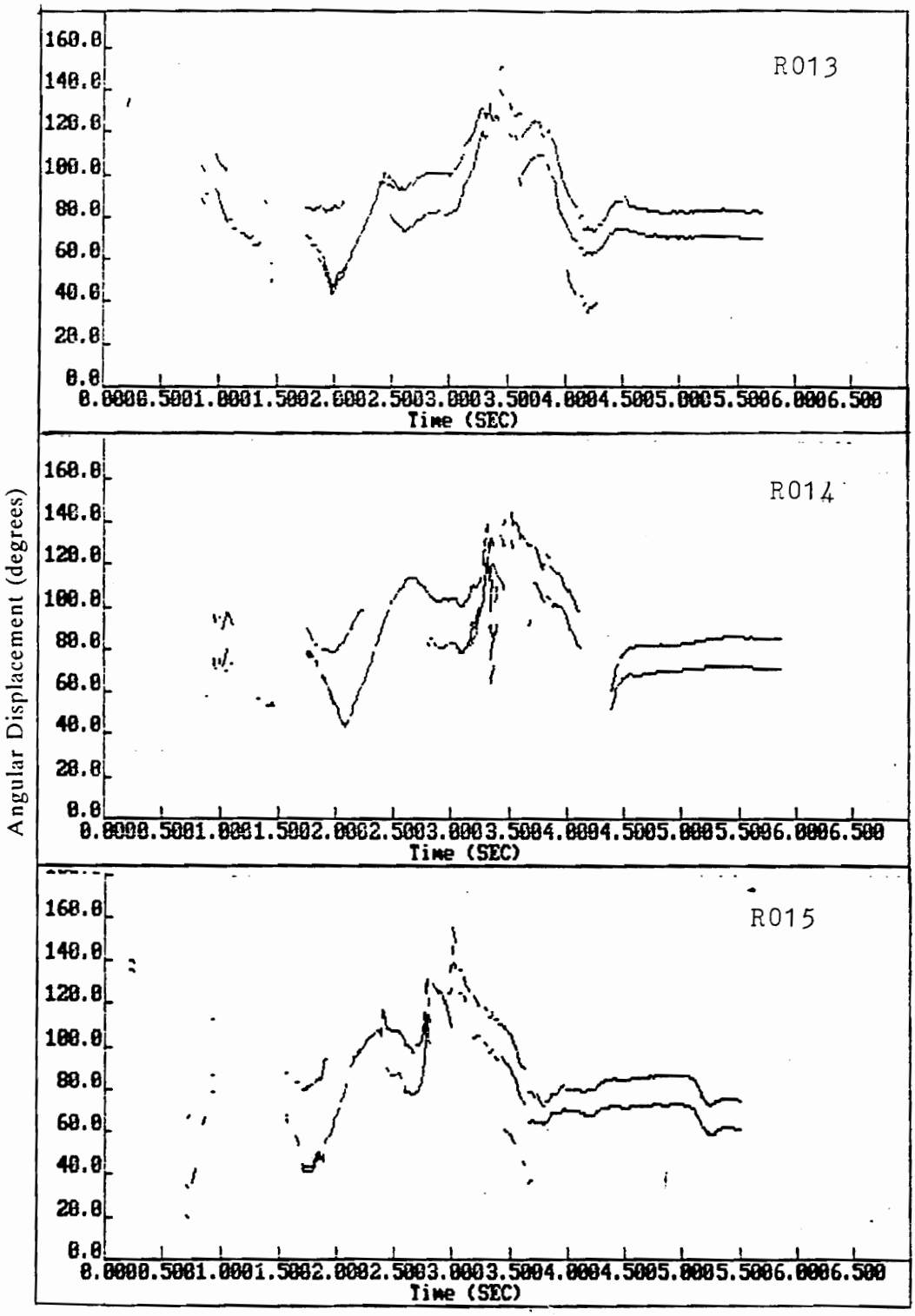

Figure I4e. Right Elbow

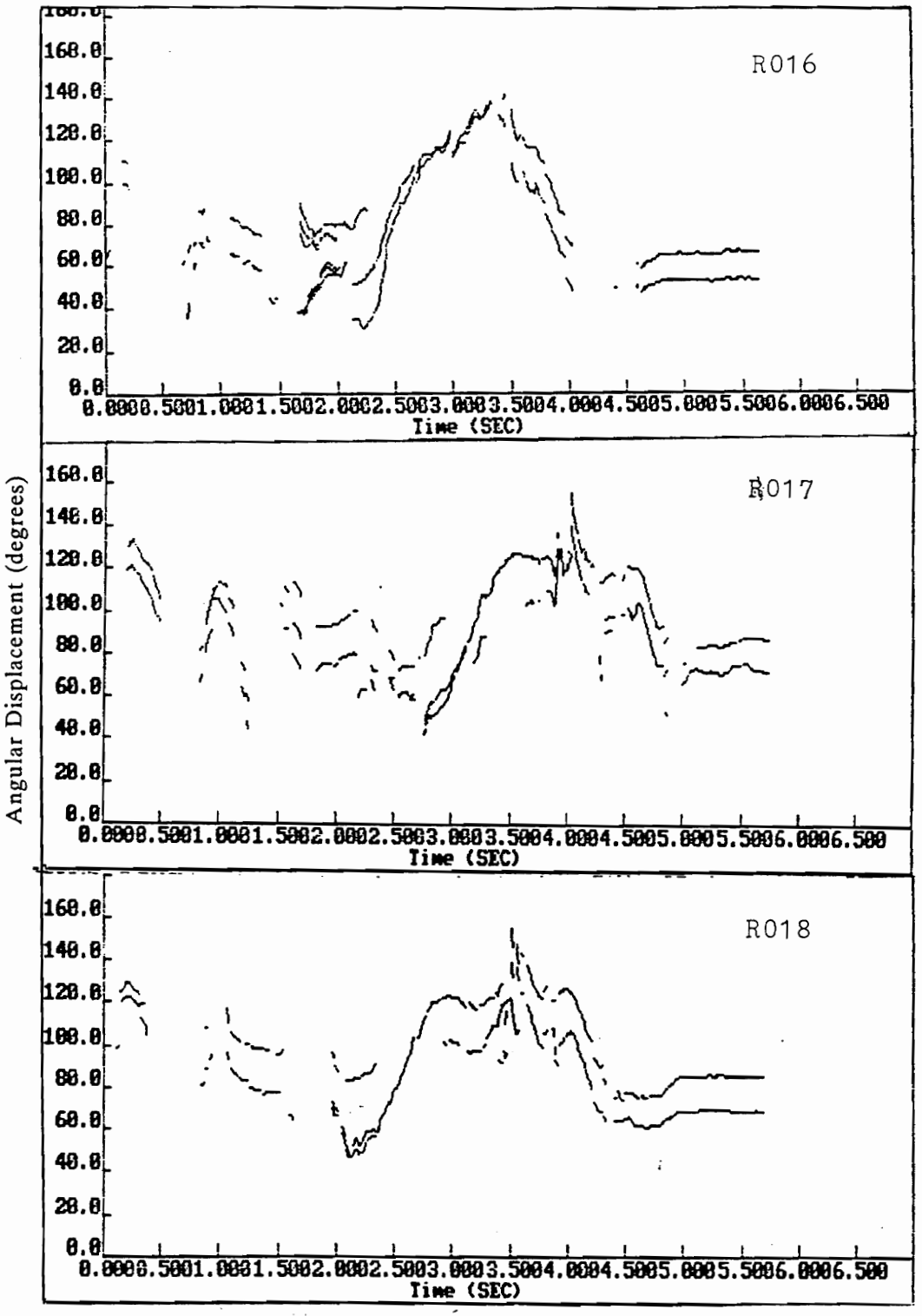

Figure I4f. Right Elbow

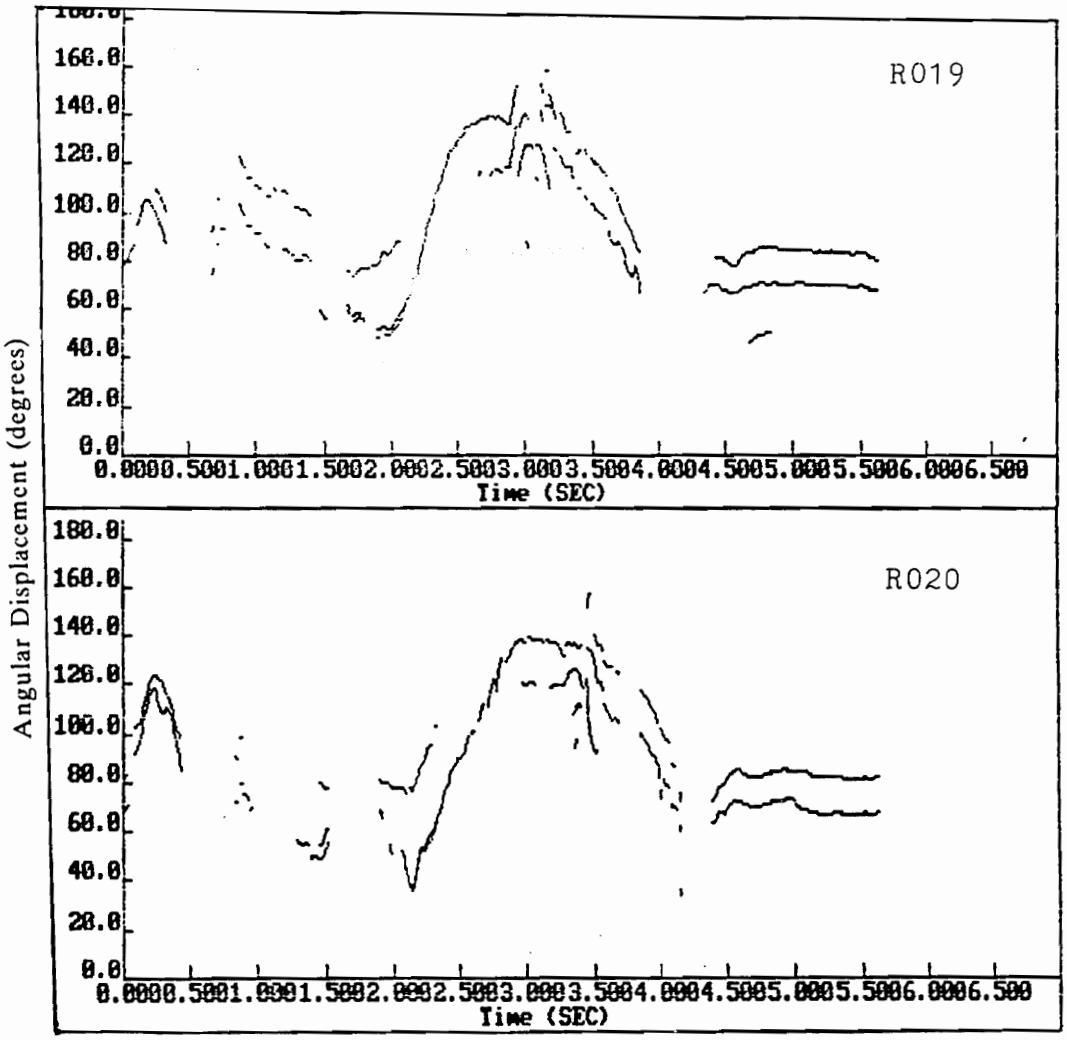

Figure I4g. Right Elbow

VITA
Wendy L. Todd

EDUCATION

M.S., Virginia Polytechnic Institute & State University (VPI&SU), Blacksburg, VA (1991). Clothing & Textiles, specializations in Apparel Design and Human Factors Engineering. Thesis: Development of a Method for Kinematic Analysis of the Doffing Process for a Specific Garment Style

B.S., Florida State University (FSU), Tallahassee, FL (1987). Clothing & Textiles, specializations in Fashion Design and Chemistry

EXPERIENCE

Graduate Teaching Assistant, Department of Clothing & Textiles, VPI&SU(1990-91)
- Taught "Introduction to Textile Evaluation Laboratory"
- Co-authored laboratory manual
- Organized and conducted labs (durability, performance, characterization)
- Researched and updated "Textile Production Processes" readings
- Proctored field trips to textile plants
- Drafted article addressing body expansion for publication with major professor

Graduate Research Assistant, VPI&SU, 1989-90
- Conducted testing on pressure sensors used for determining garment compression, and wrote manual for construction of sensors
- Assessed flat pattern capabilities of LECTRA Computer System
- Developed sleeve prototypes for indoor activewear
- Designed automobile apron
- Wrote feasiblity reports on products (auto apron) and proposed research (closet contents related to MBTI profiles)

Papers and Presentations: Development of a Method for Kinematic Analysis of the Doffing Process, Development of a Flammability Hazard Index for Nightwear, Development of a Protective Covering for Use in Eating and Driving Situations, Application of Human Factors Design Principles to a Kitchen Range

ACTIVITIES

Treasurer, Clothing & Textiles Graduate Student Assembly, VPI&SU, (1990-91)
President, Clothing & Textiles Graduate Student Assembly, VPI&SU, (1989-90)
Graduate Representative, Research and Development Committee, Department of Clothing & Textiles, VPI&SU, (1990-91)

HONORS

Cunningham Master's Fellowship, VPI&SU, (1991)
Faculty Scholarship, College of Human Resources, VPI&SU (1990)
Adelin Agnes Birney Scholarship, FSU, (1986 & 1987)
Dean's List, all semesters, FSU, (1986 & 1987)