AN ABSTRACT OF THE THESIS OF

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Gerald A. Smith

Breast discomfort during physical activity is a common phenomenon of many large breasted active women. Limited research exists concerning the efficacy of sports bras to provide support for these women. The purpose of this study was to determine the effects of breast support on several kinematic measures of running and on general comfort sensation (GCS) of the breasts while running in a group of 15 female recreational runners aged 18-58 years. Kinematics measured were stride length (SL), stride rate (SR), vertical trunk displacement (VTD), front arm angle range of motion (FA ROM), arm angle range of motion (A ROM), and vertical breast displacement. The runners were grouped according to breast cup size (B, C, & D). Three experimental conditions of breast support were used: 1) non-support (NS), 2) moderate support (MS), and full support (FS). The MS and FS conditions were created by using 2 different sport bras, engineered to give either moderate or full support. All subjects completed 3 treadmill running bouts at each level of support. Three-dimensional video analysis tracked each subject's breast and trunk motion for 10 running cycles. Under the MS and FS conditions, video data were collected at the end of 5 minutes of running, while during the NS condition only one minute of running was endurable for several subjects. The order of conditions was counter-balanced to control for possible training effects. General comfort sensation was measured during each running bout, and after 5 minutes of rest. Analysis of variance was used to compare variation among groups for all cup size group mean differences between the FS and MS conditions. Post hoc testing utilized Fisher's PLSD to identify specific group differences.

Mean differences between the FS and MS conditions within each cup size group were compared using multiple t-tests. Mean SL, SR, VTD and FA ROM were not significantly different across groups or support conditions. VBM was significantly different across support levels for heelstrikes of the foot on the same side as the breast (RVBD), $p = .0009$, and for heelstrikes of the contralateral foot (LVBD), $p < .0001$. A ROM was significant across breast size groups ($p = .01$) between the C cup group and all other groups. The absence of differences between the B and D cup size groups suggests that this measure may not have any practical significance. GCS was significantly different across support conditions for all cup size groups ($p_B = .03$, $p_C = .0003$ and $p_D = .0002$).

Despite large differences in breast motion between the full and minimal breast support conditions, the kinematic variables SL, SR, VTD, and AT ROM did not substantially change. However, this analysis compared mean values for each cup size group and some individual subjects changed kinematics substantially despite the group mean differences. The largest individual changes are illustrated in VTD data where VTD substantially decreased as breast support decreased. Therefore, future recommendations may include some individual comparisons, as it is evident that changes in breast support influence individual subjects differently.

Breast Support for the Active Woman:
Relationship to 3D Kinematics of Running

by

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CHAPTER I
INTRODUCTION

Physical fitness is regarded by many epidemiologists as a means of reduction of health risks such as coronary heart disease (CHD), hypertension, obesity, osteoporosis, insulin dependent diabetes, cancer, and other diseases, (Blair, et al., 1991; McGinnis, 1992; Shangold & Mirkin, 1988). Overall health status and physical activity patterns are correlated extensively in the literature. Physical activity has been targeted as a priority in the Nation's public health agenda released as Healthy People 2000 (Public Health Service, 1990). Studies suggest that there is a significant decrease in the risk of CHD development with regular physical activity, (Powell, Thompson, Caspersen, & Kendrick, 1987), an increase in life expectancy by 2 years, (Pekkanen, Marti, Nissinen, Tuomilehto, Punsar, & Karvonen, 1987), and a reduction of all-cause mortality by a quarter, (Paffenbarger, Hyde & Wing, 1990). Relative to obesity, a recent National Health and Nutritional Examination Survey indicated that between the ages of 20 and 74, 27% of women, and 24% of men are overweight (National Center for Health Statistics, 1991). While obesity occasionally occurs as a consequence of physical disorders, it usually develops from insufficient exercise relative to caloric intake (ACSM Guidelines, 1986). From this perspective, it is easy to recognize that the general population would benefit from an increase in physical activity. In fact, Blair et al. (1991) reported that "the number of deaths due to inactivity in the U.S. is comparable to the number of deaths caused by cigarette smoking, hypertension, hypercholesterolemia, and obesity".

Various problems that occur through participation in physical activity (injury, accessibility, expense, and anxiety over appearance), can decrease motivation, and result in a loss of desire to continue. There are nearly unlimited individual differences that affect the way we exercise, (gender, age, body type, fitness level, etc.), which may be overcome by changes in activity and equipment. Gender differences have led to the specificity of clothing and equipment for women.

In order to facilitate adherence in weight loss and activity programs, factors such as initial mood state, past weight loss maintenance experience, time management and activity preference appear to be influential (Marks, Ward, Brown, Wang, Ahmadi, & Rippe, 1992). Since running and walking are activities which are accessible (out one's back door), inexpensive, (no club fees to pay), and can fit into practically any time schedule, they may be the preferred activities for many women.

Some active (or would-be-active) women are affected by large, or sore and tender breasts which can cause embarrassment and discomfort in activities where movement of the breasts is obvious (Ryan, 1987). From this, questions arise pertaining to aspects of a woman's breast anatomy that influence exercise, and whether women refrain from activity due to the hindrance of sore and tender breasts. Several researchers have implied that excessive motion and discomfort of the breasts is problematic (Gehlsen & Stoner, 1987; Haycock, 1978; Haycock, Schierman, & Gillette, 1978; Lockwood, 1992; Ryan, 1987), and that such motion affects participation in active sports. Haycock (1978) suggested that large breasts were a particular impediment to distance running. Breast pain is prevalent for women with large breasts, but also is common for small breasted women, primarily due to pre-menstrual pain and fluid retention (Lawson, 1985; Lorentzen & Lawson, 1987).

The literature on breast motion and design of sports bras has been described in two ways: 1) surveys in which the results are used to debate the issues of the necessity of specific sports bras and which bra designs are best, and 2) biomechanical studies comparing bra styles by means of breast kinematics during exercise. Biomechanical analyses of breast motion have been executed by placing a reflective marker over one nipple and a reference marker on the lower sternum, (Lawson, 1985; Lawson & Lorentzen, 1990; Lorentzen & Lawson, 1987), or the left clavicle (Gehlsen & Albohm, 1980). It was recently demonstrated that a marker over the nipple or directly inferior to the nipple exhibits the greatest downward displacement over markers placed on other parts of the breast, (Eden, Valiant, Lawson, Himmelsbach, 1992). Past analysis of breast motion have generally dealt with the breast alone, and have not expanded into whole body kinematic and physiological affects of breast motion during exercise. Suggestions have been made that breast motion may affect performance and reduce exercise adherence. It is of interest to enlarge the scope of knowledge describing breast motion during exercise and elaborate upon performance issues as well.

Statement of the Purpose

The purpose of this study was to determine the effects of breast support on biomechanical and psychological variables of females while running. In this analysis, the biomechanical variables included stride rate, stride length, vertical trunk movement, and aspects of three dimensional breast and arm motion. A measure of perceived discomfort was also quantified by subjects during data collection.

Research Hypotheses

The hypotheses listed below describe the relationships that were anticipated from examination of the variables:

1. Lack of breast support will be associated with a change in movement patterns when compared to a full support condition.
2. Perceived breast discomfort ratings will increase as breast support decreases.
3. The most supportive sports bra condition will be associated with decreased breast motion.
4. The larger breast cup sizes (C & D) will be associated with a greater change in movement patterns as breast support decreases when compared with the smaller breast cup size (B).

Statistical Hypotheses

The following statistical hypothesis were proposed for this study:

$$H_o: \mu_1 = \mu_2$$

$$H_a: \mu_1 \neq \mu_2$$

where μ_1,and μ_2 , correspond to two conditions of breast support, (1 = full support (FS), and 2 = moderate support (MS)). The non-support (NS) condition will be used solely for descriptive purposes. Each of the following variables were analyzed:

1. stride length (SL).
2. stride rate (SR)
3. vertical trunk displacement (VTD).
4. 3D arm movement:

   a.) front arm angle range of motion. The angle range (from maximum to minimum) between elbow to shoulder and the vertical axis (FA ROM).

   b.) arm range of motion. The angle range in the sagittal plane of the upper arm with respect to the vertical axis (A ROM).
5. general comfort sensation (GCS), during and after running conditions.
6. 3D breast motion:

   a.) range of vertical movement that corresponds with the right and left heel strike independently.

   b.) range of horizontal movement.

Scope of the Study

The fifteen female subjects of the study were either recreational distance runners (running at least 10 miles/week for the past three months), or active in aerobic sports such as aerobics. Subjects were categorized into three groups of five in each breast cup size group, (B, C, & D), based on personal description of breast size. The subject's age ranged between 19 and 58 years. Data were collected in the Biomechanics Laboratory of the Department of Exercise and Sport Science, located in the Women's Building at Oregon State University.

Assumptions of the Study

To generalize the results to the larger population of female recreation runners, from the scope of this study, certain assumptions were made:

Treadmill running differs slightly from overground running in running kinematics and perceptual aspects, however it was assumed that treadmill running is similar enough to overground running that breast motion control will affect kinematics in the same manner in both cases.

Limitations of the Study

The subjects that volunteered were from a limited population due to their personal motivations involved in becoming a volunteer. Subject involvement may have been due to problems that they have experienced with discomfort, or because of a lower level of self-consciousness, than that of the general population. The subject pool of recreational runners may have limited the study since it has been observed that most distance runners have small breasts, due to the correlation of breast size to percent body fat, (Gehlsen & Albohm, 1980; Gehlsen & Stoner, 1987; Morehead, 1982), and therefore, may lack discomfort due to excessive motion, while running. There was a difficulty in recruiting subjects with large breasts, therefore large breasted active women who consistently performed aerobically in activities other than running were also considered for the study.

The treadmill has been a valid and reliable tool in collection of metabolic data, however treadmill running does not completely mirror biomechanical and physiological characteristics of running over ground (Bassett, Giese, Nagle, Ward, Raab, & Balke, 1985; Nelson, Dillman, Lagasse, & Bickett, 1972; Van Ingen Schenau, 1980). Overground running is not limited to a constant speed, grade, or surface in which similar gait patterns are exhibited throughout the workout session (Bassett et al., 1985). Likewise, the female runner may experience breast discomfort with speed and grade changes that occur during overground running, and therefore may change the way she runs, biomechanically, as a result. These differences may not occur during treadmill running. Consequently, these test conditions may be a limitation in the generalizability of the results. Treadmill accommodation periods were used to reduce the perceptual, mechanical and physiological differences found between treadmill and overground running, (Bassett et al., 1985; Nelson et al 1972: and Van Ingen Schenau, 1980).

Operational Definitions

The following is a list of definitions of terms that are used in this text:

Kinematics is the descriptive analysis of movement which encompasses displacement, velocity, acceleration and temporal relationships.

One Complete Running Stride is one full cycle from one side's heel strike to the succeeding heel strike on the same foot.

General Comfort Sensation is a subjective measure of breast comfort collected during the time of the trial. It was measured in this study by the use of a General Comfort Sensation scale, (Morris, Prato, Chadwick & Bernauer, 1985; Lawson, 1991).

Sports Bra is a bra specifically designed for use during exercise.

Stride Length in overground running is the displacement of the center of mass from heel strike to heel strike of one complete running stride (measured in meters). In the case of treadmill running, stride length (SL) was determined from running velocity (V) and stride rate (SR): SL = V / SR.

Stride Rate is the number of strides per second and is reported in Hz.

CHAPTER II

REVIEW OF THE LITERATURE

Women have become more and more active after the equal rights legislation of Title IX of the Federal Education Act, which mandated equal opportunities for women in sports twenty years ago (Haycock, 1978; Haycock, et al., 1978; Lorentzen and Lawson, 1987; Shangold & Mirkin, 1988, p. 124). The more women are involved in active sports, the more susceptible they are to injury (Bayne, 1968). Therefore, the demand for appropriate protective clothing has increased in order to facilitate the advancement of safety and performance. Gender differences have led to the specificity of this clothing and equipment for women. One of the first protective sports bras surfaced in the sports world with the introduction of the Pro + Tec protective bra in the late 1960's (Bayne, 1968). It was designed to provide support and protection needed for deflection of blows of up to 30 pounds of force from a baseball bat or tennis racket.

In 1977 Lisa Lindahl and Hinda Miller sewed two athletic supporters together as a prototype which launched the pioneer company Jogbra (Weinstein, 1991). The initial forty dozen bras that were placed on the market were sold out immediately at $8.00 per bra. Jogbra's profits were $3,000 the first year, increasing to $500,000 the second, proving that there was a waiting market for their unique product. However, research by Hunter & Torgan, in 1982, found infrequent complaints (20%) of pain or injury to the breasts among 85 intercollegiate athletes, and few of them, (10%) wore specific sports bras suggesting that sports bras aren't a necessity. To date, the literature on breast motion and injuries is primarily descriptive in nature, specifically in terms of the breast alone, and generally not expanding into whole body kinematic effects. None of the studies have attempted to relate breast motion to performance issues. Therefore, the following review of literature addresses issues of breast discomfort and how discomfort affects participation, the anatomical limitations of the breast tissue, specific injuries to the breast, biomechanical analysis of breast motion, and finally, kinematic variables typically studied in running.

Breast Discomfort Affects Participation

Several researchers have suggested that excessive motion and discomfort of the breast during exercise is a negative factor in participation of active sports (Couzens, 1992; Gehlsen & Stoner, 1987; Haycock, 1978; Haycock et al., 1978; Ryan, 1987). In a case study of a young girl with 34DD breast size, it was stated that she could not function athletically. Her discomfort from back and shoulder pain, rashes and excessive motion forced her to abandon participation in basketball and running (Couzens, 1992). Haycock, (1978) reported that large breasts were a "definite impediment to running, especially distance running." A survey of athletic trainers from 115 university physical education departments and 4 professional football programs (Haycock et al., 1978) revealed that, in general, large breasted women did not participate in sports programs. For example, they reported that 2 athletes withdrew from participation due to sore or tender breasts and a lack of availability of a well supporting bra. One trainer commented that after over 10 years of work involving track and field sports, he recalled only one or two large breasted participants, bolstering the idea that inadequate breast support contributes to nonparticipation. Thus, the benefits of fun and fitness may be lost to some women who experience embarrassment and pain from excessive breast motion when exercising in public, even in front of other women only (Ryan, 1987). A common problem with the current research is the subject pool. Most of the available information is specific to young, athletic females, who may have a lower percentage of body fat, an increased motivation for involvement, and are highly competitive (Haycock et al., 1978). However, this does not reflect the population that would benefit the most from increased fitness activity.

Limitations of the Breast Anatomy

The female breast is a mammary gland (modified sebaceous gland). The breast consists of 15-20 lobes of glandular tissue. A lactiferous duct is connected to each lobe and all intersect at the nipple (Gehlsen & Stoner, 1987). These glands are surrounded by copious amounts of connective tissue otherwise referred to as Coopers ligaments. These ligaments are described as "weak structures (that) provide the breast its primary support" (Gehlsen & Stoner, 1987, p. 13) in that they interconnect the glandular tissue to the skin and fasciae of the muscles of the pectoral region (Eichelberger, 1981; Morehead, 1982).

Variations in size, shape, and position of the breasts are somewhat, but not completely, affected by general body size. However, large fluctuations of weight, age, pregnancy, lactation, and activity of the woman (Gehlsen & Stoner, 1987; Morehead, 1982) affect the support of the breasts by distending the skin and the ligamentous attachments (Cooper's ligaments). Haycock, (1978) in describing the pendulous appearance of unsupported breasts common in primitive cultures, suggests that this is the destination of what most breasts are likely to become without support. Although some elongation occurs with progressive age, it is advocated that proper support can delay this occurrence. Breast sagging is related to a loss of skin turgor and fat tissue that declines with hormonal levels as a woman ages. In pregnancy, the breasts can increase up to three times in size, which generates a change in the tissue towards a more pendulous appearance (Haycock, 1978; Morehead, 1982; Ryan, 1987).

Hormonal stimulation prior to menstruation causes discomfort and pain in a majority of women, (Haycock, 1978). It is assumed that the active female endures elevated levels of discomfort at this time.

Injuries Specific to the Breast

Injuries to the breast are not a prevalent issue in sports medicine literature (Eisenberg & Allen, 1978; Witeside, 1980; Zelisko, Noble & Porter, 1982). In fact, most injury questionnaires do not contain a specific category for breast injury. Reported incidence of injury to the breast primarily falls under chest area or specifically listed in the "other" category on physician's inquiries. However, there are injuries that can occur due to painful blows which cause hemorrhages and contusions in the fat tissue, abrasions from the metal or plastic parts of the bra, and lacerations (Bayne, 1968; Gehlsen, 1987; Haycock & Gillette 1976; Haycock et al., 1978).

"Joggers nipples" is an injury that occurs in both women and men. It is an irritation due to abrasion of the nipple against the clothing during running. It is more prevalent in males, as females tend to wear bras when they run, but it can also occur from seams and/or material of the bra that can irritate the tissue of the nipple (Levit, 1977).

Haycock et al., in 1978 reported that 31% of trainers had athletes that suffered from injuries and complained of tender breasts after exercise. Breast tenderness is often due to excessive motion and is prevalent in large breasted women that do not have adequate breast support during high impact sports like basketball and running, (Gehlsen & Albohm, 1980; Haycock et al., 1978; Lorentzen & Lawson, 1987), whereas smaller breasted women complain more about pre-menstrual tenderness (Eichelberger, 1981; Lorentzen & Lawson, 1987).

Hunter and Torgan (1982) surveyed 85 female athletes at the University of Washington. Only 10% of the women polled wore sports bras. There were no reports of abrasions from parts of the bra. There were few (20%) who reported some pain from menstruation, or cold weather, and one basketball player had experienced a painful blow to the breast. Their research implied that specific sports bras were not necessary. The proportions of injury reported appeared low in relation to the overall number of women participating in athletics. This lack of complaints was addressed by several trainers who suggested that the female athlete may be hesitant in reporting injuries of discomfort of this kind to male trainers (Haycock et al., 1978). There is also a problem in generalizing the results of previous studies to the normal population. Many of the studies in this area are have used subjects that are college age or elite athletes, and hence may have excluded large breasted participants (Haycock et al., 1978). Consequentially, there is some controversy as to whether these reports of injuries to the breasts are significant enough to require further deliberation.

Injuries and discomfort are not all that may be affected by lack of breast support during exercise. Prior, Jensen, Yuen, Higgins, & Brownlie (1981) studied the effects of breast motion and its role in increasing prolactin levels during exercise. As prolactin levels increase, menstruation tends to decrease, or cease entirely. They found that there were differences between elite runners and cyclists in that runners experienced more breast motion and prolactin levels subsequently increased during this type of activity as compared to cycling. This suggests a rationale for the lower documented incidence of amenorrhea (absence or suppression of menstruation) among elite cyclists as compared to elite long distance runners.

The development of products that are intended to minimize breast injuries has stimulated research regarding the effectiveness of breast protective equipment. Recently, Lawson (1991) compared comfort, agility, metabolic cost, and mechanical reactions to applied missile impacts between four chest/breast protectors. She found that use of the breast protectors did not affect metabolic cost of running. Differences were found in agility course performance, suggesting that aggressiveness may be enhanced by the feeling that the breast is protected against impact. Thermal discomfort and skin wettedness were not perceived as being different than a control of no breast protection, even though skin temperatures were elevated with protective bra use. Two of the protectors (FemGard and JBI) were not different from the control bra in general comfort sensations. Shock attenuation and deformation properties were evaluated with closed-cell foam and rigid polyethylene protectors. The first was superior in shock attenuation when the missile mass was light, and the second excelled in impact protection against heavier missile masses.

Biomechanical Analysis of Breast Motion

According to the American Society for Testing and Materials (ASTM), supportive bras "are those intended to limit the displacement of breast tissue during physical activity." (ASTM, 1990, p.342). The biomechanical analysis of breast motion has been addressed by several investigators, (Gehlsen & Albohm, 1980; Haycock et al., 1978; Himmelsbach, Valiant, Lawson & Eden, 1992; Lawson, 1985; Lawson & Lorentzen, 1990; Lawson, 1991; Lorentzen & Lawson, 1987). All researchers emphasized the need for substantial support for larger breasted women due to the association between excessive breast motion and discomfort.

Haycock et al., (1978) used a group of 5 subjects to film breast displacement using 16mm movie film at a frame rate of 100 Hz. Each subject walked (3 mph) and jogged (6 mph) on a treadmill inclined at 1%. Markers designated the nipples, and frontal and sagittal views were filmed. Data were collected in three conditions of breast support: no bra, the subject's regularly worn bra, and a specifically fitted sports bra whose design characteristics depended on the subject's chest and breast size. Both of the two specifically fitted styles were made of nylon tricot and included an elastic band along the lower edge of the bra. The more supportive style selected for the larger breasted women had a more rigid (less elastic) construction, molded cups, and fastened with hooks in the back. All subjects preferred the specific sports bra over their own bra, particularly the larger breasted women who initially considered their selected style uncomfortable to wear. Visual comparisons of displacement demonstrated that the specifically fitted sports bras noticeably reduced vertical and lateral motion of the breast. It was noted that without support, the breasts that were particularly large and pendulous in size "rose up and then slapped down against the chest wall with considerable force at each complete step." Based on their findings, the researchers suggested that vertical displacements should not exceed 2 cm for comfort.

Gehlsen & Albohm, (1980) had a sample of 40 female subjects (mean age 23.3 +/- 4.7 years), ten in each breast cup size A, B, C, and D. Subjects were filmed with reference dots on the nipple and left clavicle while running on a flat grade at 6 mph. Differences in breast displacement were found among 8 different sports bras, but no significant differences in mean displacement were found among cup size groups. The range of vertical displacement was 1.4- 3.3 cm, with an average difference of 0.64 cm between large and small breasts. Gehlsen and Albohm concluded that the primary criterion for a good sports bra should be support qualities, and that the range of vertical motion for comfort was not to exceed 2 cm.

A comparison of 8 different sports bras was conducted to examine the relationship between perceptions of comfort, support, and biomechanically derived support characteristics (Lawson, 1985; Lawson & Lorentzen, 1990). The researchers placed reference markers on the nipple location and the lower sternum of 59 subjects of cup sizes A, B, C, and D. Subjects ran on a treadmill (level grade) at 6 mph. The bras that rated well on perceived comfort, also tended to rate well on perceived support. However, the perception of support and the empirical analysis of support were not highly correlated. The authors noted that different breast sizes demand different support and design qualities, that bras for each cup size should be designed according to the requirements of the specific size, and that a single style and fabrication seldom works well for all cup size groups, (Lawson, 1985; Lawson & Lorentzen, 1990).

A recent analysis of breast motion in running involving 3D analysis was carried out at the Nike Sport Research Laboratory (Eden, Valiant, Lawson & Himmelsbach, 1992; Himmelsbach, Valiant, Lawson, & Eden, 1992). The researchers compared four different sports bras using fifteen female subjects during running at a freely chosen stride rate (mean = 85 Hz.), and a fixed stride rate of 96 Hz. All subjects wore size 36 C bras. There were significant differences between the four bra designs in upward, downward (which exhibited the most movement), medial and total vertical displacements. Mean vertical displacements for each bra ranged from 2.06 to 3.09 cm. More movement was observed with the freely chosen stride rate when compared to the quicker fixed stride rate. The bras most effective at reducing vertical motion were not necessarily also effective at reducing medial/lateral motion. From this study it could not be concluded which movement (medial/lateral or vertical) was most important in reducing discomfort.

A parallel analysis of the Nike data involved peak breast accelerations (Himmelsbach et al., 1992). Infrared diodes on nipple, proximal sternum, and on two accelerometers vertically aligned on the sternum and breast, adjacent to the nipple were used to obtain displacement data collected at 333 Hz with a Watsmart active marker system. Peak accelerations were differentiated from displacement data, and compared with accelerometer measures. Sports bras that are designed to compress the breasts against the body produced lower mean peak acceleration (1.9-2.0 g's) than a conventionally designed bra which simply encapsulates each breast (2.3 g's).

All studies comparing sports bra styles have shown that there are differences in support characteristics of various bra designs. Several of the biomechanical analyses of breast motion have made suggestions regarding types of bras that provided good support, and discussed specific design features believed to be influential in reducing breast motion. Lorentzen & Lawson (1987), recommended that sports bras for larger breasts need a more rigid (less elastic) support structure than those designed for smaller breasts, and Haycock et al., (1978) concluded that larger breasted women need additional support in the bra cup. The most supportive bras secure the breast close to the body. A double layer of fabric over the breasts increases support, and the fabrication that is used will optimally be a high modulus knit with low extensibility (Lawson, 1985; Lawson & Lorentzen, 1990; Lorentzen & Lawson, 1987).

Sports bra design specifications should also vary according to the arm range of motion demands of specific sports (Lawson, 1985; Lawson & Lorentzen, 1990; Lorentzen & Lawson, 1987). Sport motion patterns that include overhead reaching of the arms should incorporate stretch in the strap to reduce "riding up" of the bra's rib band onto breast tissue. Bras for sports without this overhead activity do not need the same amount of ease in the strap, and provide optimum support when the straps are non-elastic and are attached to a non-stretch cup. Straps should be designed in a T-, Y-, V-, or narrow U-back configuration so that they do not slip off the shoulder during activity. Because the increased skin temperature and humidity accompanying vigorous exercise can exacerbate tactile sensitivity, bra fabrics should be chosen for their non-irritable characteristics. Researchers (Gehlsen & Albohm, 1980; Lorentzen & Lawson, 1987; Ryan 1987) suggest that active women should look for non-irritating fabrics on seams and straps that are next to the skin and durable construction that will withstand frequent laundering.

Running Kinematics

The biomechanical analysis of running involves many different types of experimental studies. The literature includes investigations of how the body moves in terms of linear and angular joint displacements, velocities, accelerations, stride length, stride frequency, and center of mass movement. Peter Cavanagh commented that "twenty years ago the notion that the mechanics of distance running was a valid topic of scientific study would probably have been disputed by many people." However, "as running for exercise rather than for competition has become popular, more and more scrutiny has been brought to bear on this classical form of human locomotion" (Cavanagh, 1990, p. 1). Running mechanics have been primarily evaluated in a lab setting where the runner performed on a treadmill. In order for the results to be effectively generalized to an overground setting it is necessary to evaluate the differences that exist between treadmill and overground running. There have been a number of studies that compare the differences in these two settings (Bassett, et al., 1985; Nelson, Dillman, Lagasse, & Bickett, 1972; and Van Ingen Schenau, 1980). Nelson et al., (1972) analyzed 16 male runners on an overground situation of an indoor running ramp, and on a treadmill. They observed kinematic adjustments described as an increase in the support phase and decrease in the flight phase due to an over extension of the forward foot strike pattern on the treadmill. The factors that previous studies have focused on point to the possibility that treadmill running may have lower oxygen demand compared to overground running (at the same speed), (Bassett et al., 1985; Nelson et al., 1972; Van Ingen Schenau, 1980).

The typical relationship between stride rate, stride length and velocity is that stride length increases as velocity increases, and maintains this until near maximum speeds, where the increase in velocity is mainly due to increases in stride rate, (Cavanagh, 1990, p. 38).

Running Mechanics and Running Economy

Running economy is defined as "the aerobic demand ($\dot{V}O_2$) of submaximal running" (Morgan & Craib, 1992). It has been noted extensively that when comparisons of individuals with the same $\dot{V}O_2$ max values, the runner who is more physiologically economical, will outperform the other (Daniels & Daniels, 1992; Morgan & Craib, 1992). Differences exist between male and female runners in $\dot{V}O_2$ max, running economy, body composition, performance and other characteristics. Men traditionally outperform women over all running events by roughly 10%, (Daniels, Krahenbuhl, Foster, Gilbert, & Daniels, 1977). $\dot{V}O_2$ max sex differences have been reported as high as 19% for highly trained runners, (Daniels et al., 1977). Moreover, women are consistently lighter, shorter, have more body fat, and lower $\dot{V}O_2$ max (ml/kg/min) values than men, (Bhambhani & Singh, 1985; Bransford & Howley, 1977; Cureton, Sparling, Evans, Johnson, Kong, & Purvis, 1978; Cureton & Sparling, 1980; Daniels, Krahenbuhl, Foster, Gilbert & Daniels, 1977; Daniels & Daniels, 1992; Howley & Glover, 1974; Nelson, Brooks & Pike, 1977).

Howley and Glover (1974), compared metabolic differences of men and women during walking and running. The subjects (8 males and 8 females) subjectively chose their most comfortable speed of walking and running. The average speed of walking for both men and women was 82 ± 3 m/min, and running was 195 ± 25, and 137 ± 4 m/min for men and women respectively. Running required 80 % more energy/kg of body weight than walking, and females' energy expenditure per kg of body weight was significantly higher than for males ($p < .01$). It was theorized, but not measured, that females had more vertical displacement for both activities, which required more energy. Falls & Humphrey (1976) measured energy expenditure of walking and running in women. They found values of 5.16 to 6.7 kcal/kg/hr for walking, which was slightly higher than values previously obtained with men. They also calculated lift and lift work against gravity during walking and running. Females elicited a 11-12% lower lift work, and shorter strides at walking speeds, than a previous study of males, however, stride lengths were consistently shorter and lift work was 11-12 % greater for females during running. Bransford and Howley, (1977), also presumed that women had more vertical oscillation then men. They compared untrained and trained males and females and found that trained subjects ran more economically, than the untrained. In regression analysis, the regression line comparing oxygen uptake ($\dot{V}O_2$) and running speed for the trained males was significantly lower ($p < .05$) than all other groups, and untrained females and all other groups ($p < .05$). There was a non-significant difference ($p > .05$) between untrained males and trained females $\dot{V}O_2$ submax. The subject's training backgrounds revealed that females trained at a lower intensity, with less supervision, and less total exercise time, (averaging 30 miles per week compared to 75 miles per week for the males). Trained females elicit a wider variance of $\dot{V}O_2$ submax as speeds increase towards maximum, where male's variance decreases, (Daniels et al., 1977).

An established way of predicting performance has been $\dot{V}O_2$ max, however in a homogenous group of male runners (with $\dot{V}O_2$ max values ranging between 67.3 and 72.72 ml/kg/min) 65.4% of the variation of performance in a 10K race was explained by variation in running economy (Conley & Krahenbuhl, 1980). Similarly, Daniels & Daniels (1992), compared a male and female with the same $\dot{V}O_2$ max values (78.7 & 78.8 ml/min/kg respectively), and determined, according to their individual economy ratings, that running a marathon at 83.7% of each runner's $\dot{V}O_2$ max, the female would finish more than 12 minutes behind the male. However, Conley, Krahenbuhl, Burkett, & Millar (1981) found no correlation between running economy and 10K running times. The estimated pace of 84.7% (+/- 5.9%) of $\dot{V}O_2$ max during a 10K was not significantly different from male counterparts.

Cureton, et al. (1978), analyzed young distance runners, (four males and two females), and the effects of added weight on aerobic capacity and running performance. They hypothesized that the measure of cardiovascular capacity ($\dot{V}O_2$ max (ml/min/kg body weight)) is confounded by individual differences in body fatness. The added weights were 5%, 10%, and 15% of body weight and were secured by a harness on the torso. It did not appear that the added weight affected the mechanics of running during stress tests and 12 minute runs, but did result in showing significant effects of added body fat on aerobic and running performance. The correlation between performance and $\dot{V}O_2$ max decreases when it is expressed in ml/kg(FFW)/min, (where FFW is fat free weight). $\dot{V}O_2$ max and 12 minute run distance decreased systematically with each increment of added weight. The effect of each 5% increment of added weight decreased the 12 minute run distance by an average of 89 meters. Cureton & Sparling (1980), added weight to male runners which were paired with females in order to equate body fat percentages for each pair. Without added weight, there was a sex difference of 7.5% body fat, 34% $\dot{V}O_2$ max, and a 20% difference between 12 minute run distances. With added weight, the differences decreased to 23% for $\dot{V}O_2$ max values, and 14% for 12 minute run distances. They concluded that the higher percent fat for women decreases the aerobic capacity when it is expressed relative to total body weight, there is greater physiological stress, and $\dot{V}O_2$ max is reached at a lower speed. Therefore the energy requirement at any given speed is increased due to this sex specific fat. In contrast, Falls & Humphrey (1976) found no differences in energy expenditure between males and females when expressed per unit of body weight.

After comparing female adults and children, Rowland & Green (1988), suggested that weight related $\dot{V}O_2$ submax levels are impaired by running economy and not simply better aerobic fitness. A similar analysis between males compared energy cost per step. When calculated $\dot{V}O_2$ costs for each step were equal between adult and prepubertal males, differences were related to increased stride frequency, and lower running economy for children (Rowland, Auchinachie, Keenan, & Green, 1987).

While there are obvious individual differences between runners (e.g. training condition, body composition, and $\dot{V}O_2$ max), individual variations of running kinematics affect performance. However, there have been many conflicting results as to the specific mechanics responsible for economic running. This is primarily due to the difficulty in controlling all of the many factors that affect performance in order to achieve a causative relationship (Williams, Krahenbuhl, & Morgan, 1991). Frederick (1985), suggested that biomechanists need to further synthesize the reasoning behind mechanically economical movement.

Nelson, Brooks, & Pike (1977), studied elite male and female distance runners. Females were shorter, lighter, and had shorter legs; they also experienced shorter strides (96.5% of males) and higher stride rates, (.14 steps/sec across all velocities). However, when these values were related to leg length, females elicited greater distance per stride than males. Females also differed by 4% longer flight times and less absolute distance. The primary finding of this study was that females varied considerably from men in their running style, suggesting that females were not simply a "scaled down" version of men.

The determination of which specific mechanics are responsible for economic running has been analyzed in two ways (Williams, 1985). The first is to alter one or two variables, and compare the result in energy use (Cavanagh & Williams, 1982). The second is to measure two distinct groups of individuals that are separated by physiological characteristics. Then mechanics are measured for each group and comparisons are made as to the best set of variables responsible for more economic running (Bhambhani & Singh, 1985). The problems that occur with the first technique, are that the alteration of one variable affects other countless mechanical variables that are associated with running.

Cavanagh and Williams (1982) studied the effects of stride length (SL) on oxygen uptake during distance running. They hypothesized that shortening and lengthening the stride affects the muscles in their force-velocity relationships, with the anticipated effect of changes in oxygen use. Seven stride lengths were determined by ± 6.7%, ± 13.4%, and ± 20% of leg length from a freely chosen SL. The stride lengths were manipulated by foot contact following the sound of a metronome. A regression line of a best fit (quadratic curve, U shaped) was adjusted for each subject comparing stride length changes and $\dot{V}O_2$ (where stride length was the explanatory variable, and $\dot{V}O_2$ was the response variable). The optimum of each was located at the base of the U. However, small deviations in optimum stride length minimally affected oxygen consumption. There was a low correlation of optimal SL with leg length, suggesting that prediction of SL by use of leg measurement on a general population of runners was not practical. The lack of statistical significance in determining small changes in $\dot{V}O_2$ that result from mechanical changes is due to the problems with effect size, and sample size. In order to determine a small difference, statistically, a large sample is needed. However, a modest change in $\dot{V}O_2$ submax of 2% over the duration of a marathon, may increase time substantially (Williams, et al., 1991).

Some research has begun to focus on training for improved running economy. Messier and Cirillo (1989) used verbal feedback with adult novice female runners that were assessed as having mechanical defects in their running techniques. Each subject completed 15 twenty-minute treadmill runs which resulted in modest changes in running mechanics. Knee flexion increased, which aids in the dissipation of impact forces, and reduces inertial properties of the leg during the swing phase. Findings also included a non-significant reduction in elbow angle (closer to the preferred 90 degree angle), and a decrease in upper extremity rotation about a vertical axis, which reduced excessive motion. At pre-test most women understrided. The experimental group increased their non-support time (NST) and decreased their support time (ST) over that of the controls. The ratio of ST/NST = 4.8 was close to reported ratios of elite female marathon runners. No significant change in oxygen consumption or RPE (rate of perceived exertion) was found.

Morgan, Martin, Craib, Caruso, Clifton & Hopewell (1992) attempted to train 6 males and 3 females for more efficient running economy. The subjects were chosen by their freely-chosen step length (FCSL) ($\bar{x}$ optimal stride length = -9.81 % of leg length from the FCSL) which was determined to be "uneconomical." They provided 3 weeks of audio and visual feedback which resulted in a more optimal SL and decreased aerobic demand of running.

The biomechanics of running economy, synthesized by Frederick (1985), composed a table of factors that have been shown to affect running economy. Some of the direct evidence links economy to wind, grade, circadian rhythms, running surface, carrying excess weight, body weight, and stride length. Other evidence, indirectly relates leg length, center of mass excursion, foot contact time, arm motion, and trunk angle of inclination. It is difficult to ascertain if there is a single mechanism responsible, or a specific related group which affects running economy. The mechanical factors that appear to be associated with economical running are variations of the following: vertical oscillation of the center of gravity, arm motion, trunk inclination, and support time. Also rear-foot-strikers are more economical than fore-foot-strikers (Atwater, 1973; Frederick, 1985).

Summary

In conclusion, there is a paucity of literature clarifying the possible performance mechanisms involved with economic running in the female runner. There are definite sex differences in body composition, $\dot{V}O_2$ max values reported in ml/kg/min and l/kg(FFW)/min, running economy, and running styles. Women are not "scaled down" versions of men. These differences extend anatomically beyond what has been measured previously. A woman's breast size, and/or levels of breast discomfort during exercise affects participation, and adherence to exercise programs. Consequentially, the health risks associated with a lack of regular, aerobic exercise can escalate. The design and analysis of sports equipment has been enhanced through biomechanical analysis. It is of interest to extend the understanding of design and performance of sports bra products by how they affect the potential mechanisms involved in creating a more economical running profile.

CHAPTER III
METHODS

The relatively few studies evaluating the biomechanical performance of sports bras results in a lack of established methodology for comparing breast motion and running kinematics. However, several related test methods can be integrated to develop a relevant method for this research. For example, the testing procedures for treadmill accommodation suggested by Bhambhani & Singh (1985) were applied in this study. The use of treadmill accommodation techniques have been recommended in order to reduce perceptual differences and ensure stable gait mechanics (Bhambhani & Singh, 1985; Morgan & Craib, 1992; Morgan, Martin, Krahenbuhl & Baldini, 1991; Williams, Krahenbuhl & Morgan, 1991). The kinematic variables typically used in temporal analysis and breast motion studies were integrated to provide the answers to the questions of interest to this research.

This chapter describes the characteristics of the subjects, the protocol utilized for data collection, instruments, apparatus, and statistical treatment of data. In addition, methods for estimating kinematic variables resulting from changes in selected breast support are outlined.

Description of Subjects

Fifteen female volunteers were selected on the basis of their physical characteristics (three groups of five according to breast cup size), and training background (they had run habitually at least 6-10 miles per week for the previous three months, or were aerobically active and could maintain a running pace of 2.86 m/s (6 mph)). The range of ages was 19 to 58 years. A full list of Anthropometric data is summarized in Appendix E.

Due to the nature of the study, complete randomization processes of subject selection could not be employed. The women were volunteers, which suggests that they may have some motives for involvement in the study. Interested subjects were screened for running and exercise history, physical breast measurement, and medical risk factors.

Informed consent was approved through the Oregon State University Human Subjects Committee prior to testing. The study complied with the University's research policies for the treatment of human subjects. After thorough examination and explanation of the procedures and use of the data, the subjects were asked to sign the informed consent form, a copy of which is provided in Appendix A.

Procedures

Each subject was screened for possible cardiorespiratory disorders by filling out a medical questionnaire (Appendix A) where positive answers on questions 1, 3, 4, 5, or 6 disqualified the subject from participation. Breast size, and the possibility of excessive stretching of the breast tissue due to multiple pregnancies and/or extreme weight fluctuations were addressed through personal discussion. A personal information sheet was then filled out including age, children, breast-feeding, and exercise history.

Prior to data collection, subjects discussed and signed the informed consent form which encompassed procedures, risks, benefits and the confidentiality of data and results. An estimation of body fat was used to further describe our sample. Each subject was informed of the procedure, and given the estimate information. Three sites were measured, (triceps, suprailliac, and abdominal). Each site was measured three times by the same technician. The calculations determined an estimate of each subject's body fat percentage.

The three conditions of breast support that were utilized in this study were as follows:

1) non-support (NS)
2) moderate support (MS)
3) full support (FS)

The breast was unsupported in the NS condition, with a marker covering the nipple. The MS and FS conditions were created through provision of two different sports bra styles designed to give either moderate or full support. The criterion of breast support for the MS and FS conditions was derived from both empirical biomechanical data and resulting style recommendations found in previous research on the supportive characteristics of sports bras (Lawson & Lorentzen, 1990, Lawson, 1985 and Lorentzen, & Lawson, 1987). Design specifications of the bra used to create the FS condition included the use of a high-modulus knit material with low extensibility, non-stretch double-layer cup fabric, straps that did not stretch between the top of the cup and the top of the shoulder, and a wide rib band that did not ride up onto the breast tissue. The full support bra used for the B cup subjects was the Supplex®, (style # 89), while the C and D cup subjects wore the Sportshape™ Sport Top®, (style # 72), both styles are produced by Jogbra® Sports Bras. Both of these bras provided similar support characteristics to their respective cup size group subjects..

The sports bra used to create the MS condition did not include the supportive elements listed above. It was constructed of all-elastic fabrics and trims, and did not include additional support structures. However, it was a product that was marketed as a sports bra by an independent label, and represented the most prevalent style available to women in 1993.

Each subject was issued the FS sports bra for the week prior to their data collection time. She was instructed to wear the bra as much as possible during the week, while participating in running and other sports related activities.

The treadmill accommodation was then performed. The accommodation session involved three 10-minute level runs, at the constant speed of 2.86 m/s, (6 mph), with rest periods five minutes in duration between each run. This was accomplished while wearing the FS bra and the subject's usual running shoes. Accommodation runs were performed in order to reduce random errors from perception and orientation changes with the use of the sports bra and the treadmill, (Morgan et al., 1991; Nelson et at., 1972).

The General Comfort Sensation (GCS) scale was utilized during the accommodation period to familiarize each subject with the scale. It is described in detail later in this chapter. A brief explanation of the scale and the protocol that followed was introduced. Then, it was presented during the last 2 minutes of each 10-minute running period, and also during the rest periods between minutes 4 & 5. Each subject was asked the question: "Thinking specifically of the breast area, which sensation most closely reflects your present breast comfort sensation?" The subject indicated the number that most closely represented their comfort perception. The researcher confirmed the number indicated by reiterating the number selected. The GCS scale was also presented during the test conditions in the same fashion, and at the same time periods of running (the last 2-minutes of each treatment, and minutes 4 to 5 of rest following the test).

The subject was then informed by the researcher the time and day of the test session, (the order of the treatments was undisclosed). The order of the treatments was counterbalanced to control for possible training effects. The same pair of running shoes was required to be worn in each test situation by each individual subject.

For the test situations, the lab was screened to ensure privacy for the subjects. Camera placement around the treadmill was optimized by a pilot study (Figure 1). The set-up included the use of three cameras: Two cameras were used together for 3D video collection. The cameras were approximately 100 degrees apart, and were focused primarily on the subjects' torso. The third camera was used solely for 2D video collection of foot strikes.

The second visit to the laboratory began with an overview of the requirements of the day's testing. The GCS scale and test protocol were reiterated, and the first breast support treatment was disclosed. The subject was outfitted with retroreflective tape, marking several points of interest on the sternum, left breast, shoulder and mid-humerous, (Figure 2).

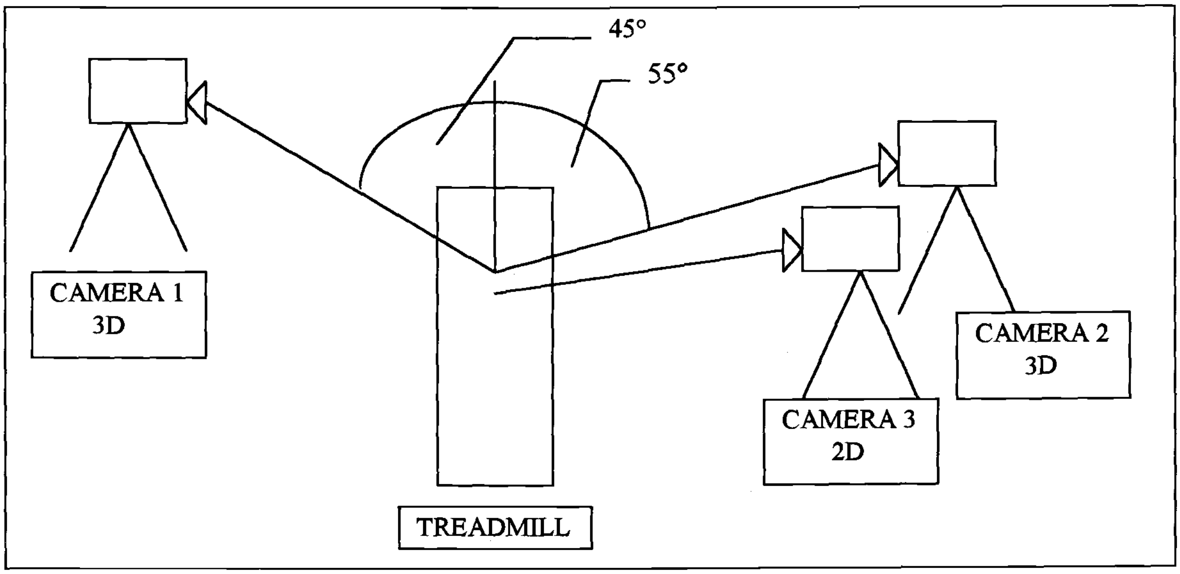

Figure 1: Camera Set-up.

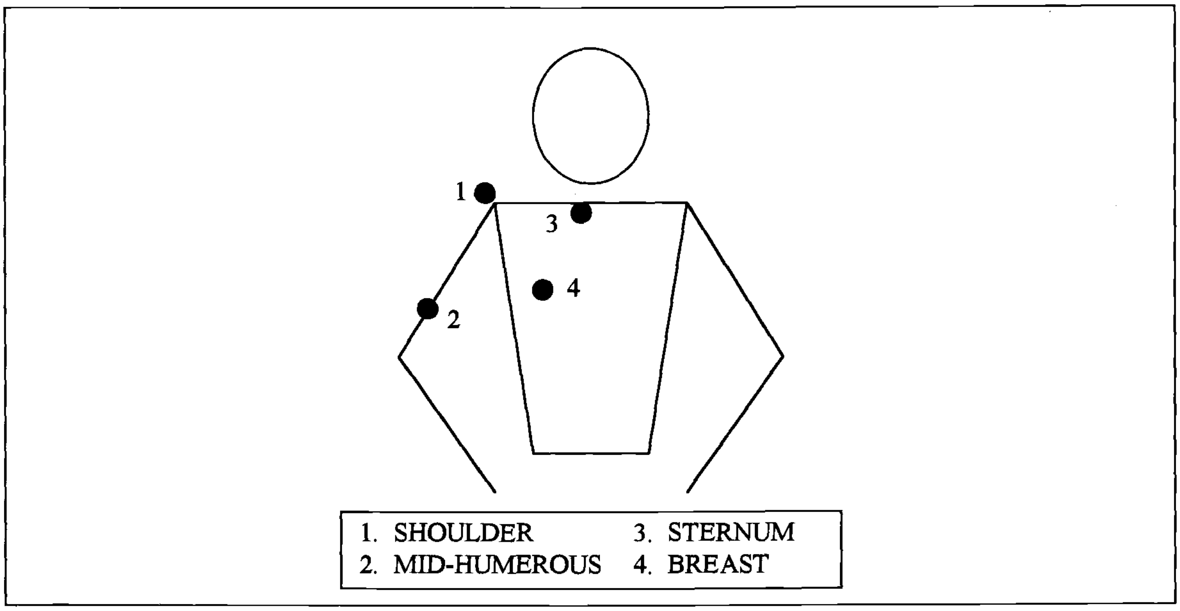

Figure 2: 3D Spatial Model.

The test protocol consisted of: First an 8-minute warm-up at a walk or slow running pace, and then a block of 5-minutes of running with video data collection and GCS scale information taken during the last 2 minutes of the test. A signal by the researcher prior to the last 3 minutes of running, and visible in each camera's view was given as an indication of a reference point to aid in integration of the timing of each camera. The GCS scale was presented again between minutes 4 and 5 of rest. The rest period was 5-minutes in length. The subject was then given the second breast support treatment, and the above protocol was duplicated. Identical procedures were used in the third breast support treatment. Each subject performed all three of the support conditions. Due to a great amount of discomfort of the breasts during the NS condition, it was anticipated that a five minute run could not be sustained by subjects with larger breasts (C and D cup sizes). Therefore all subjects were filmed from the beginning of the NS condition in order to extract data from this condition, where only one minute of running was endurable for several subjects.

After the data collection was performed for each subject, the researcher digitized the video records. The same 5 strides from each camera's view were digitized, and the 3D camera views were merged by the DLT method (Abdel-Aziz & Karara 1971) in order to estimate 3D motion of the points of interest in each treatment. The 2D camera records analyzed the heel strike only during the same time frame.

Kinematic measurements of stride frequency, stride length, and vertical trunk displacement were averaged over 5 consecutive running strides. Arm motion was analyzed in frontal and sagittal projections: Front arm angle range of motion (FA ROM), [the angle range from maximum to minimum between elbow to shoulder and vertical segments, (Figure 3)], and arm angle range of motion (A ROM), [the angle range in the sagittal plane of the upper arm with respect to the vertical axis, (Figure 4)]. These arm angles were also averaged over 5 consecutive running strides.

Three dimensional breast motion included vertical and horizontal breast displacement. Vertical breast displacement was further defined for heel-strikes of the foot on the same side as the breast (RVBD) and for heel-strikes of the contralateral foot (LVBM). The point on the sternum was used as an indication of trunk vertical

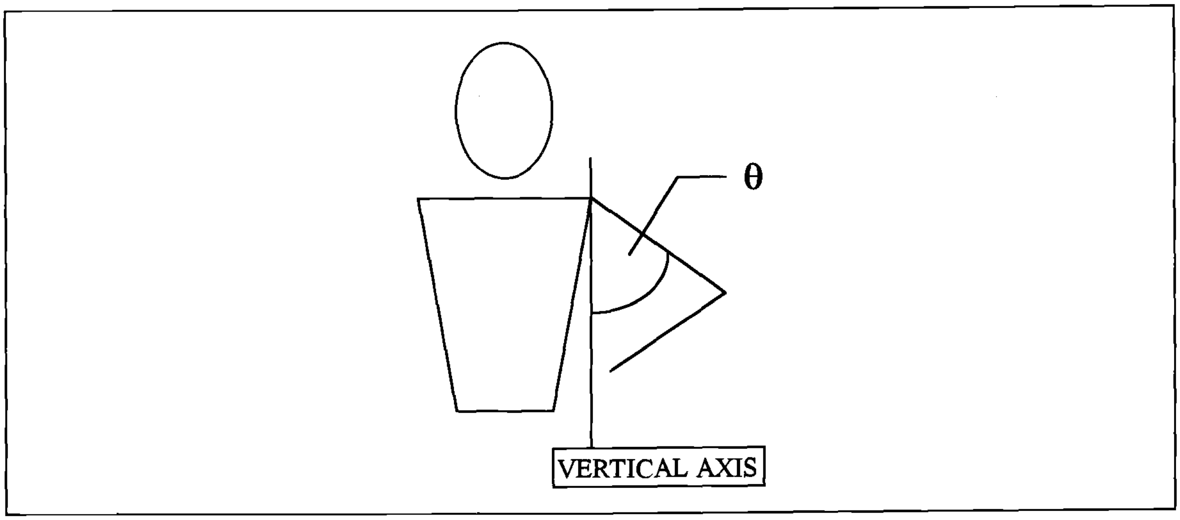

Figure 3: **Front View of Front Arm Angle ROM**

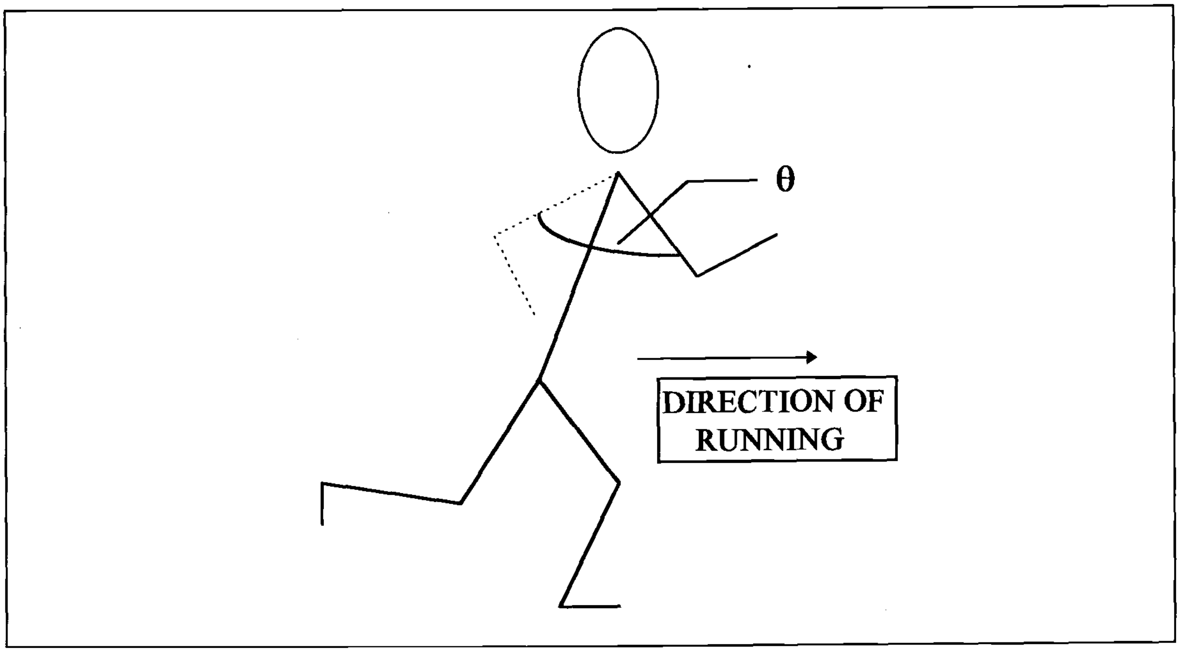

Figure 4: **Sagittal View of Arm Angle ROM**
(represented by θ)

displacement (VTD), and as a reference to find breast motion relative to the body. This served to reduce differences in breast motion due to differences in skin turgor and stride variations between subjects (Lawson & Lorentzen, 1990; Lorentzen & Lawson, 1987).

Instruments and Apparatus

The following is a list of the instruments and apparatus that were used in this research:

General Comfort Sensation Instrumentation

The perceptual sensitivity that humans possess has been shown to consist of approximately seven distinctive ranks of discernment. Cena & Clark (1981) suggest that fewer than seven gradations is too limited when applied to comfort research. Therefore, research on comfort in the study consisted of seven numerical stages. The General Comfort Sensation Scale, (Table 1), has been used extensively, including breast motion research (Morris, Prato, Chadwick, & Bernauer, 1985, and Lawson, 1991). The GCS scale has been described as a global measure of comfort which includes fit, fashion, design, and general impression of texture, (Lawson, 1991).

Percent Body Fat Estimation

An estimate of body fat was utilized to further describe the subjects beyond breast size, age, height and weight. Skinfold calipers were used in this estimate. The device is used to measure three sites, (Triceps, supraillium, and thigh), three times to get an average measure for each site. The cite averages were used in a regression equation developed by Jackson & Pollock, (1985) along with measurements of weight and age in this estimation of body fat percent.

Table 1: General Comfort Sensation Scale

1. comfortable
2.
3. slightly uncomfortable
4.
5. uncomfortable
6.
7. very uncomfortable

Video and Digitizing Apparatus

Two Panasonic S-VHS Reporter movie cameras, Model AG-450, were used to collect 3D biomechanical data in this study. Two-dimensional data were collected using a Panasonic Digital System camera model WV-D5100. The cameras operated at a frame rate of 30 Hz and collected 60 fields per second with electronic shutter time of 1/1000 sec.

The PEAK Performance Motion Measurement System, software version 5, from Peak Performance Technologies, Inc., displays the video field by field in order to determine the points of interest on the image. The researcher manually determined each point of interest by setting up a spatial model, and either a semi-automatic or manual mode of digitization was used.

The Direct Linear Transformation (DLT) method as described by Abdel-Aziz & Karara (1971), transformed 2D image coordinates from two cameras into 3D coordinates. This process consisted of three phases:

1). The calibration phase used a control structure that contained twelve control points. It covered the complete field of view of each of the two torso cameras. The three dimensional coordinates of each control point were accurately known.

2). The PEAK system was used to calibrate each camera's field of view. The process determined 11 camera constants.

3). Finally, the files from each camera view were combined to give 3D coordinates for each point of interest.

The Butterworth 4th order (double pass) digital filter is a recursive filter which was used to filter out the random errors introduced by measurement (Wood, 1982). The recursive routine uses previous raw and filtered data points in order to smooth the data.

The Peak system utilized this system at an optimal frequency which ranged between 2 and 9 Hz. The calculation of the optimal filter parameter uses the *Jackson Knee Method,* (Peak Performance Technologies, Inc. 1992).

Video Recording

A pilot study was performed in order to analyze the best position of the video cameras. The cameras that were used for three-dimensional (3D) data collection were located approximately 45 - 55 degrees off of the anterior frontal plane of the subject. The two-dimensional (2D) camera was used exclusively to collect heel-strikes, and was placed to obtain a sagittal plain view.

The two 3D cameras were focused on only the torso area. Points of interest that were included in this view were the right nipple, the sternum, right anterior shoulder, and the right mid-humerus (see figure 1). Retroreflective tape was placed on these points in order to utilize the semi-automatic mode of digitizing in the PEAK Motion Measurement system.

Experimental Design

A 3 by 2 repeated measures design with three treatment groups, (B, C, and D breast cup sizes) and 2 levels of treatments (minimal support, MS, and full support, FS) were used in the statistical analyses. The non-support (NS) condition was analyzed for descriptive purposes but was not included in the statistical comparison of means as considerably more variability was observed for the NS condition. The order of the trials were counterbalanced to control for possible training effects.

Statistical Treatment

This analysis was specifically aimed at indicating whether there are differences between two support conditions, FS and MS, under any of the kinematic variables tested. The primary statistical analysis was a single factor ANOVA comparing the difference of FS and MS where the null hypothesis was (FS - MS) = 0. This determined whether support level had an overall effect upon any of the kinematic variables tested. Data from the NS condition were not included in the statistical comparison of mean values as considerably greater variability of kinematic characteristics was observed for the non-supported condition. However, mean values for each variable under the NS condition have been included in the results for descriptive purposes.

When a significant difference was found, a follow-up examination of the data used Fisher's PLSD to determine differences between breast size groups for each of the kinematic variables tested. A second follow-up compared the effect of support at each breast cup size using paired t-tests with a pooled variance.

For all tests, level of significance was set at a moderately liberal level ($\alpha = .05$) based on the small sample size in each group and the variability typically observed in running kinematics. ANOVA and PLSD follow-up tests were carried out using StatView 4.0 software (Abacus Concepts, StatView, 1992) running on an Apple Macintosh IICX.

CHAPTER IV
RESULTS AND DISCUSSION

The primary purpose of this study was to determine the effects of breast support on biomechanical characteristics of females while running. In this analysis, two dimensional (2D) and three dimensional (3D) data were used throughout five consecutive running strides with three levels of breast support (full, minimal, and no-support). The 3D biomechanical variables included vertical and horizontal breast displacement, vertical center of mass displacement, front arm angle range of motion, and arm angle range of motion. Stride length and stride rate were calculated from 2D video analysis. An additional purpose was to compare the subjective measure of general comfort sensation (GCS) between each level of breast support while running.

Anthropometric Data

The fifteen subjects who participated in this study were volunteers and female students or faculty of Oregon State University as well as residents of Corvallis, Oregon. Acceptance into this study required habitual recreation in the form of running or aerobics over the three months prior to the study, and the ability to maintain the 2.86 m/s (6 mph) pace on the treadmill. The subjects were divided into three experimental groups according to bra cup size (B, C, and D).

The mean physical characteristics of the entire group of subjects and of each cup size group (B, C, and D) are summarized in Table 2. The mean age of the entire group of subjects was 31.6 ± 10.0 years. The mean height for the entire group was 1.69 ± 0.04 m. The mean weight was 66.2 ± 9.4 kg . On average, the B and D cup groups were taller than the total group mean, the B cups being the tallest, and the D cup group was heavier on average than the total group mean. The mean percent body fat was 23.46 ± 6.04 %. There was a trend for percent body fat to increase with breast size; this corresponds with

Table 2: Anthropometric Characteristics of Subjects

	ENTIRE GROUP	B CUP	C CUP	D CUP
AGE (yr.)	31.67(10.02)	33.80 (7.57)	37.40(10.98)	23.80(4.87)
HEIGHT (m)	1.69(.04)	1.70(.03)	1.67(.03)	1.70(.04)
WEIGHT (kg)	66.19(9.39)	63.87(9.64)	63.23(5.18)	71.49(10.133)
BODY FAT (%)	23.46(6.04)	22.38(6.89)	23.60(3.76)	24.40(6.76)

previous findings that there is a positive correlation between breast volume and body fat percentages, (Pollock, Laughridge, Coleman, Linnerud & Jackson, 1975).

Only two of the 15 subjects had children. One of the B cup subjects had two children, while the other subject (C cup) had one child. In each case the children were breastfed.

Twelve of the 15 subjects were active runners. The other three subjects varied their work outs between swimming, aerobics and biking. All had been consistently active over the 3 months previous to testing, and could maintain the 2.86 m/s required running pace.

Kinematic Data Analysis

Each kinematic variable of the hypotheses was tested independently and will be individually addressed in the following sections. Individual t-tests using pooled variance were used to test the differences between the Full and Minimal Support conditions for each of the variables tested. One-way analysis of variance (ANOVA) methods were used to test differences across groups between the Full and Minimal Support conditions for each of the variables tested. The ANOVA, Fisher's PLSD and t-tables for each variable are presented in Appendix B.

Subsequent to videotaping, a control structure was filmed by each of the torso cameras. Calibration was accomplished by utilizing the Peak Performance System to digitize the positions of the spheres that were within the area of interest on the control structure and then inputting the coordinate data into the Peak System for each camera. Direct linear transformation (DLT) reprediction errors were about 4 mm for each subject and are included in Appendix F. Accurate 3D coordinate data taken within the area of the control structure were then collected.

Stride Length

Stride length in overground running is the displacement of the center of mass during one complete running stride. In the case of treadmill running, a less direct determination of stride length is required. Because running velocity (V) is determined by stride length (SL) and stride time (ST), if velocity and time are known, then stride length can be calculated ($SL = V * ST$). In this study, treadmill running was controlled to be 2.68 m/s and ST was determined by counting the video frames per complete stride.

Mean stride length across groups and support conditions was about 1.9 m. Mean stride lengths in the Full and Minimal Support conditions were not significantly different ($p = .20$). Mean stride lengths for each cup size group between the Full and Minimal Support conditions were not significantly different for any group (one tailed $p_B = .91$, $p_C = .11$, and $p_D = .46$). While the No Support condition was not included in the statistical comparison of means, it is worth noting an apparent trend for the larger size groups (C and D) that stride length decreased as support decreased. The B group stride lengths were relatively unaffected by support level. Table 3 summarizes the group and support level statistics for stride length. Figure 5 graphically depicts the mean values for each group and support condition.

Table 3: Stride Length, Mean(SD)

SIZE GROUP	FULL SUPPORT	MIN SUPPORT	NO SUPPORT	OVERALL
	STRIDE LENGTH (meters)			
B	1.87(.137)	1.91(.100)	1.89(.084)	**1.89**
C	1.94(.191)	1.90(.150)	1.85(.172)	**1.90**
D	2.05(.215)	2.05(.208)	1.94(.304)	**2.01**
OVERALL	**1.95**	**1.95**	**1.89**	**1.93**

Table 4: Stride Rate, Mean(SD)

SIZE GROUP	FULL SUPPORT	MIN SUPPORT	NO SUPPORT	OVERALL
	STRIDE RATE (Hz.)			
B	1.44(.11)	1.41(.07)	1.42(.06)	**1.42**
C	1.39(.14)	1.42(.12)	1.46(.15)	**1.42**
D	1.32(.14)	1.32(.13)	1.41(.21)	**1.35**
OVERALL	**1.39**	**1.38**	**1.43**	**1.40**

Stride Rate

Stride rate is the number of strides per second and is reported in Hz. In this study, treadmill running was controlled to be 2.68 m/s and ST was determined by counting the video frames per complete stride. Mean stride rate across groups and support conditions was about 1.4 Hz. Mean stride rates in the Full and Minimal Support conditions were not significantly different ($p = .17$). Mean stride rates for each cup size group between the Full and Minimal Support conditions were not significantly different for any group (one tailed $p_B = .94$, $p_C = .14$, and $p_D = .46$). While the No Support condition was not included in the statistical comparison of means, it is worth noting an apparent trend for the larger size groups (C and D) that stride rate increased as support decreased. The B group stride lengths were relatively unaffected by support level. Table 4 summarizes the group and support level statistics for stride rate. Figure 6 graphically depicts the mean values for each group and support condition.

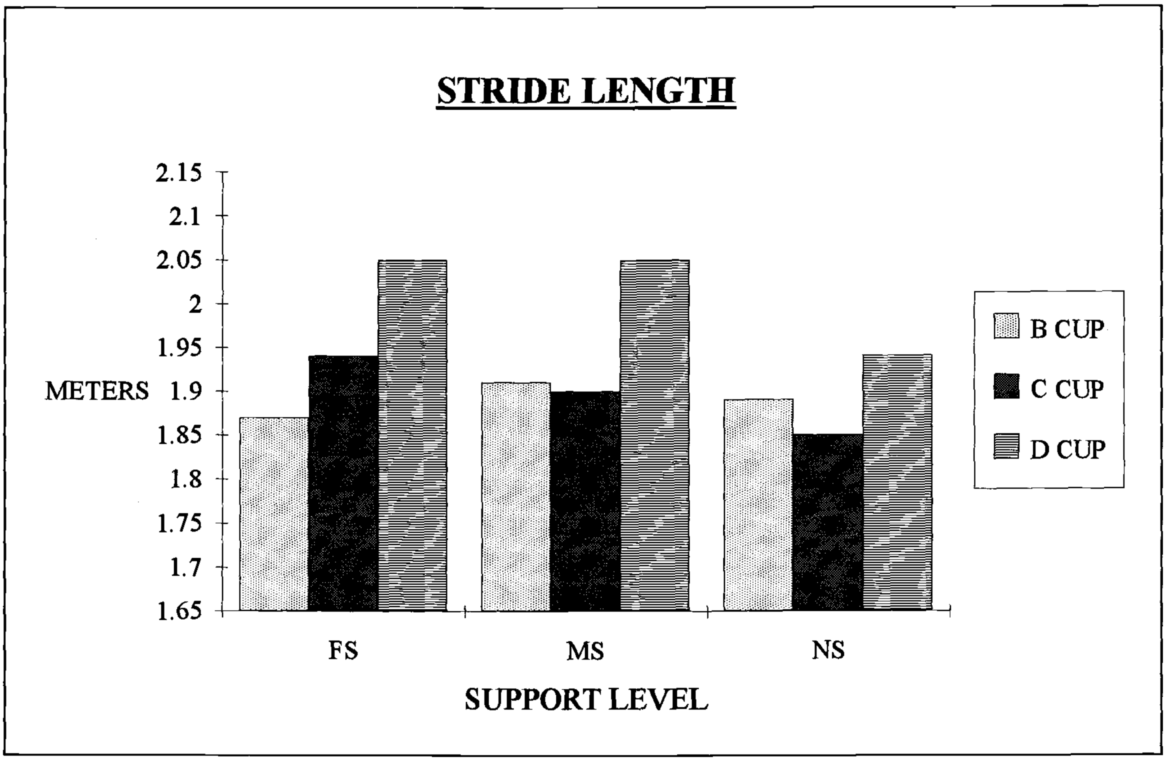

Figure 5: Mean Stride Length

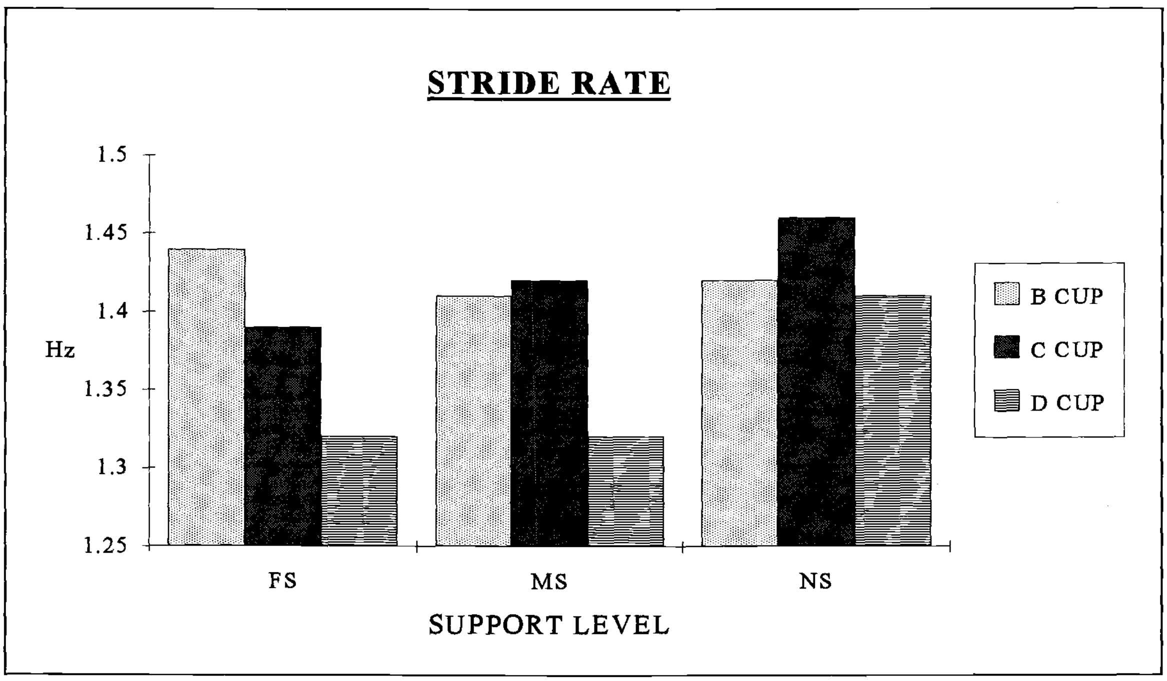

Figure 6: Mean Stride Rate

Table 5: Vertical Trunk Displacement, Mean(SD)

	VTD (mm)			
SIZE GROUP	FULL SUPPORT	MIN SUPPORT	NO SUPPORT	OVERALL
B	71.3(28.1)	83.3(15.1)	73.8(5.7)	**76.1**
C	90.7(34.3)	81.7(16.8)	56.9(25.3)	**76.4**
D	111.1(25.0)	108.7(23.6)	76.5(37.1)	**98.8**
OVERALL	**91.0**	**91.2**	**69.1**	**83.8**

Vertical Trunk Displacement

Vertical Trunk Displacement (VTD) was estimated and averaged over 5 strides from the point of reference on the sternum.. Mean VTD across groups and support conditions was about 83.8 mm. Mean VTD in the Full and Minimal Support conditions were not significantly different ($p = .23$). Mean VTD for each cup size group between the Full and Minimal Support conditions were not significantly different for any group (one tailed $p_B = .91$, $p_C = .15$, and $p_D = .39$). While the No Support condition was not included in the statistical comparison of means, it is worth noting an apparent trend for the larger size groups (C and D) that VTD decreased as support decreased. The B group VTD was relatively unaffected by support level. Table 5 summarizes the group and support level statistics for vertical trunk displacement. Figure 7 graphically depicts the mean values for each group and support condition.

Front Arm Angle Range of Motion

Front Arm angle range of motion (FA ROM) was measured as the angle range from maximum to minimum between elbow to shoulder and the vertical axis in the frontal plane. It was hypothesized that the subjects may use their arms in a protective manner (holding them closer to the body) as breast support decreased, in order to protect from discomfort. Mean FA ROM across groups and support conditions was about 16.3

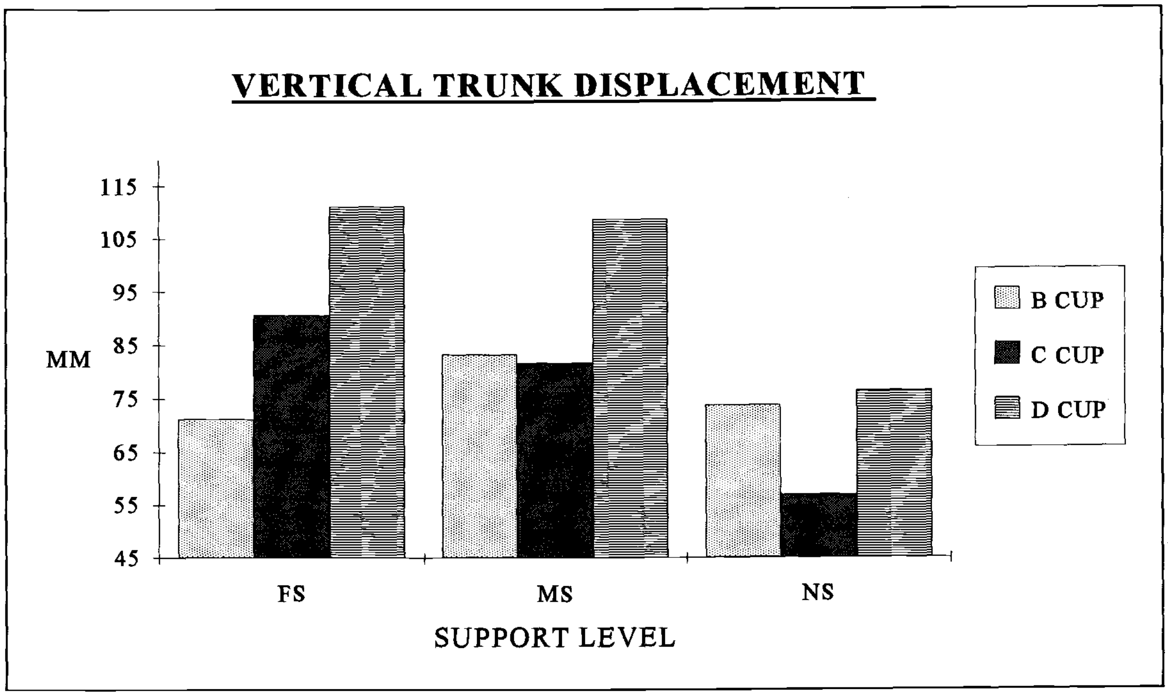

Figure 7: Mean Vertical Trunk Displacement

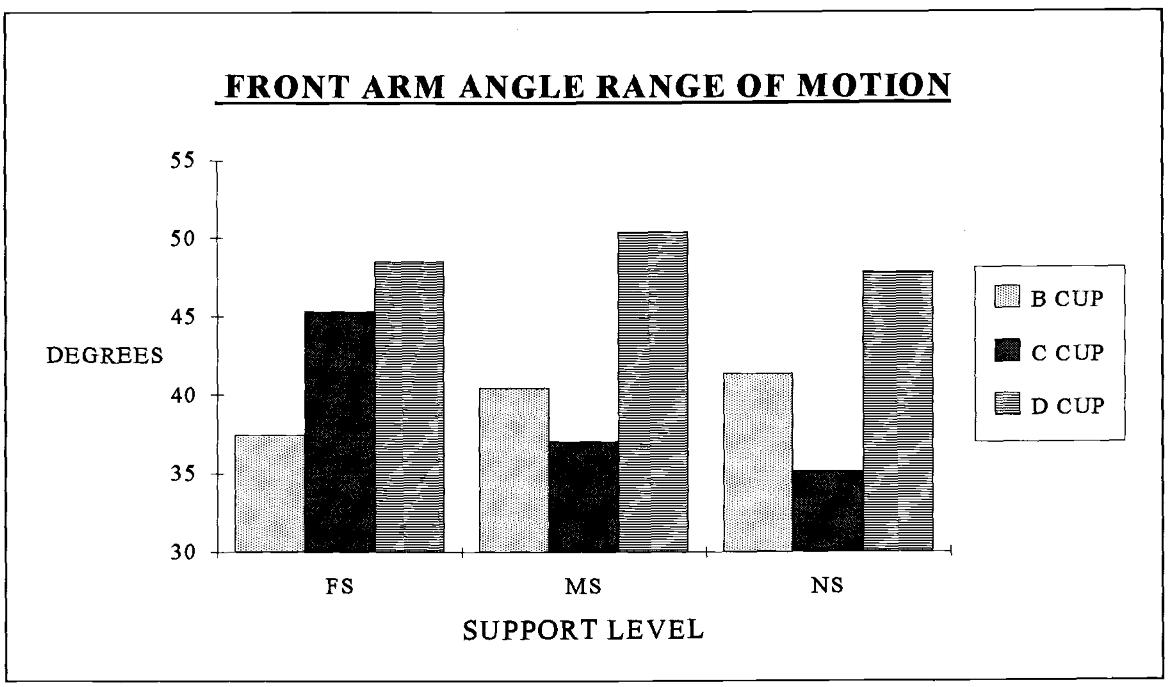

Figure 8: Mean Front Arm Angle ROM

degrees. Mean FA ROM in the Full and Minimal Support conditions were not significantly different ($p = .32$). Figure 8 graphically depicts the mean values for each group and support condition. Mean FA ROM for each cup size group between the Full and Minimal Support conditions were not significantly different for any group (one tailed $p_B = .33$, $p_C = .67$, and $p_D = .93$). Table 6 summarizes the group and support level statistics for FA ROM. Figure 8 graphically depicts the mean values for each group and support condition.

Arm Angle Range of Motion

Arm Angle Range of Motion (A ROM) is the angle range in the sagittal plane of the upper arm with respect to the vertical axis. It was hypothesized that the subjects may use their arms in a protective manner (restricting the front to back swinging motion) as breast support decreased, in order to diminish discomfort. Mean A ROM across

Table 6: Front Arm Angle Range of Motion, Mean(SD)

	FA ROM (degrees)			
SIZE GROUP	FULL SUPPORT	MIN SUPPORT	NO SUPPORT	OVERALL
B	14.6(4.0)	13.5(4.0)	12.9(4.1)	**13.7**
C	14.2(3.7)	16.6(4.4)	17.9(5.3)	**16.2**
D	17.9(6.0)	21.7(6.6)	17.7(8.5)	**19.1**
OVERALL	**15.6**	**17.3**	**16.2**	**16.3**

Table 7: Arm Angle Range of Motion, Mean(SD)

	ARM ANGLE ROM (degrees)			
SIZE GROUP	FULL SUPPORT	MIN SUPPORT	NO SUPPORT	OVERALL
B	37.4(10.3)	40.4(9.4)	41.3(9.3)	**39.7**
C	45.3(6.6)	37.0(4.4)	35.1(9.3)	**39.1**
D	48.5(8.9)	50.4(11.9)	47.8(20.3)	**48.9**
OVERALL	**43.7**	**42.6**	**41.1**	**42.6**

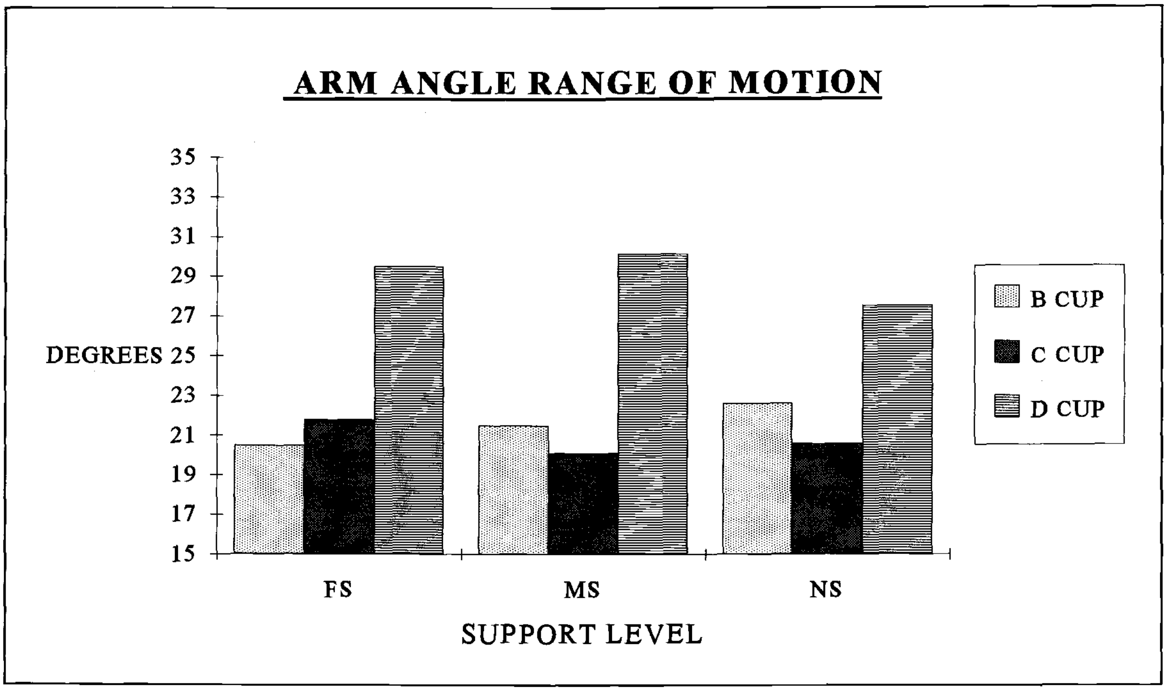

Figure 9: Mean Arm Angle ROM

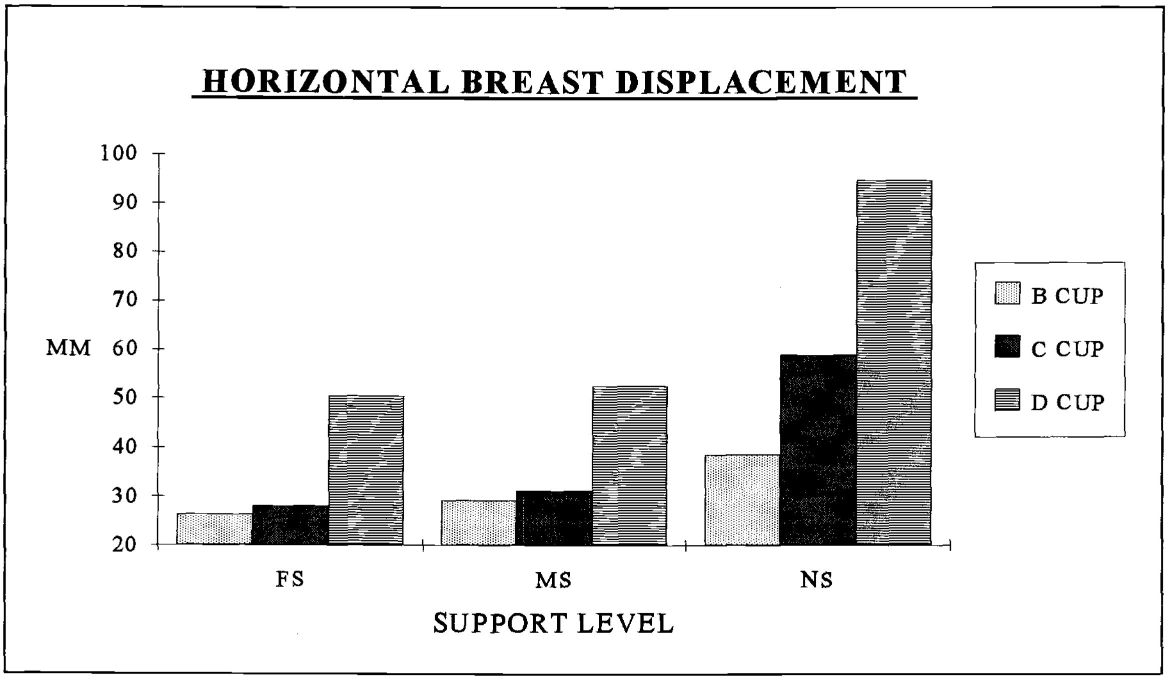

Figure 10: Mean Horizontal Breast Displacement

groups and support conditions was about 42.6 degrees. Mean A ROM in the Full and Minimal Support conditions was significantly different ($p = .01$). Because a significant F was found, pairwise differences were investigated using the LSD method. The results identified significant differences in A ROM between the B and C cup groups and the C and D cup groups, but no difference between the B and D size groups. The lack of significance between the B and D cup size groups suggests that this measure may not have any practical meaning. Mean A ROM for each cup size group between the Full and Minimal Support conditions was significantly different for the C cup group, (one tailed $p_C > .0009$), however, no significant differences were found for the B and D groups, (one tailed $p_B = .91$, and $p_D = .81$). Table 7 summarizes the group and support level statistics for A ROM. Figure 9 depicts the mean values for each group and support condition.

Horizontal Breast Displacement

Mean Horizontal Breast Displacement (HBD) across groups and support conditions was about 45.6 mm. Mean HBD in the Full and Minimal Support conditions was not significantly different ($p = .98$). Mean values of HBD for each cup size group between the Full and Minimal Support conditions were not significantly different for any group (one tailed $p_B = .22$, $p_C = .21$, and $p_D = .28$). Table 8 summarizes the group and support level statistics for HBD. Figure 10 graphically depicts the main values for each group and support condition.

Table 8: Horizontal Breast Displacement, Mean(SD)

	HBD (mm)			
SIZE GROUP	FULL SUPPORT	MIN SUPPORT	NO SUPPORT	OVERALL
B	26.4(10.3)	29.3(17.3)	38.6(17.4)	**31.4**
C	28.1(8.8)	31.2(7.9)	58.9(25.3)	**39.4**
D	50.4(16.3)	52.6(18.1)	94.7(3.4)	**65.9**
OVERALL	**35.0**	**37.7**	**64.1**	**45.6**

Vertical Breast Displacement

Vertical breast displacement was analyzed separately for each corresponding heel strike. Observation of the displacement curves of several subjects portrayed a difference in curve shape dependent upon heel strike. When the breast is supported, apparently there is greater breast displacement when the breast that is measured is on the same side as the heel that is striking (Figures 13, 14 and 15). All of the graphs begin on the left heel strike. The displacement from minimum to maximum is predominantly lower during the breast displacement resulting form the left HS, when compared to that of the right HS. This variation between separate heel strikes is reduced as breast support decreases. Therefore, vertical breast displacement was analyzed separately for same-side and opposite-side heel strikes.

Mean Right Vertical Breast Displacement (RVBD) across groups and support conditions was about 53.9 mm. Mean RVBD in the Full and Minimal Support conditions were significantly different ($p = .0009$). Because a significant F was found, pairwise differences were investigated using the LSD method. Significant differences in RVBD

Table 9: Vertical Breast Displacement (Right HS), Mean(SD)

	RVBD (mm)			
SIZE GROUP	FULL SUPPORT	MIN SUPPORT	NO SUPPORT	OVERALL
B	20.7(12.2)	30.1(12.6)	42.2(6.8)	**31.0**
C	26.2(8.1)	46.6(8.8)	58.5(27.5)	**43.8**
D	51.5(7.2)	90.8(10.2)	118.6(9.2)	**87.0**
OVERALL	**32.8**	**55.8**	**73.1**	**53.9**

Table 10: Vertical Breast Displacement (Left HS), Mean(SD)

	LVBD (mm)			
SIZE GROUP	FULL SUPPORT	MIN SUPPORT	NO SUPPORT	OVERALL
B	16.7(10.8)	22.8(10.1)	40.5(4.8)	**26.7**
C	21.6(4.3)	41.5(10.8)	57.0(20.6)	**40.0**
D	39.6(8.8)	76.3(6.7)	117.9(18.6)	**77.9**
OVERALL	**26.0**	**46.9**	**71.8**	**48.2**

between the B and D cup groups and the C and D cup groups were identified, but no difference between the B and C size groups. While the No Support condition was not included in the statistical comparison of means, it is evident that across all size groups, RVBD increased as support decreased. Mean RVBD for each cup size group between the Full and Minimal Support conditions were significantly different for all groups (one tailed $p_B = .02$, $p_C < .0001$, and $p_D < .0001$). Table 9 summarizes the group and support level statistics for RVBD. Figure 11 graphically depicts the mean values for each group and support condition.

Mean Left Vertical Breast Displacement (LVBD) across groups and support conditions was 48.2 mm. Mean LVBD in the Full and Minimal Support conditions were significantly different ($p < .0001$). Because a significant F was found, pairwise differences were investigated using the LSD method. Significant differences in LVBD between the B and C, the B and D , and the C and D cup groups were identified. While the No Support condition was not included in the statistical comparison of means, it is evident that across all size groups, LVBD increased as support decreased. Mean LVBD for each cup size group between the Full and Minimal Support conditions were significantly different for all groups (one tailed $p_B = .04$, $p_C < .0001$, and $p_D < .0001$). Table 10 summarizes the group and support level statistics for LVBD. Figure 12 graphically depicts the mean values for each group and support condition.

Previous findings used the combined right and left heel strikes for values of breast displacement. Previous research suggests that vertical displacements should not exceed 2 cm for comfort, (Gehlsen & Albohm, 1980; Haycock, Shierman, & Gillette, 1978). However this number was exceeded in the FS condition on average during the heel strike corresponding to the same side as the breast, particularly in the larger breast cup size groups (see Appendix C).

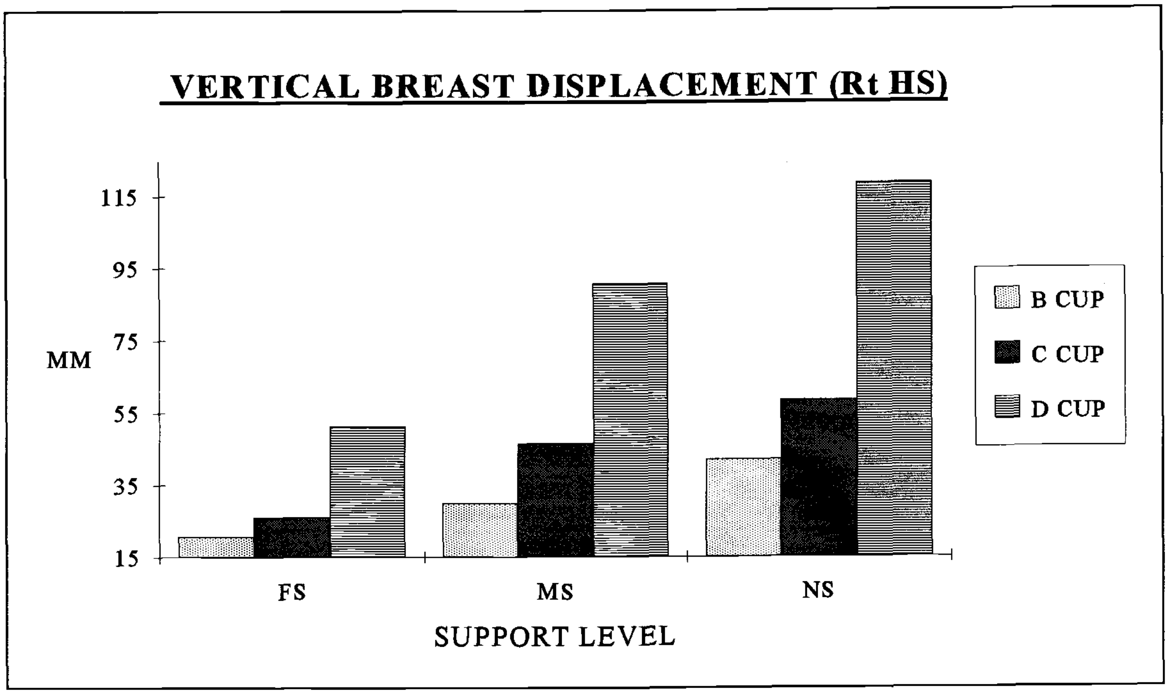

Figure 11: Mean Vertical Breast Displacement (Right HS)

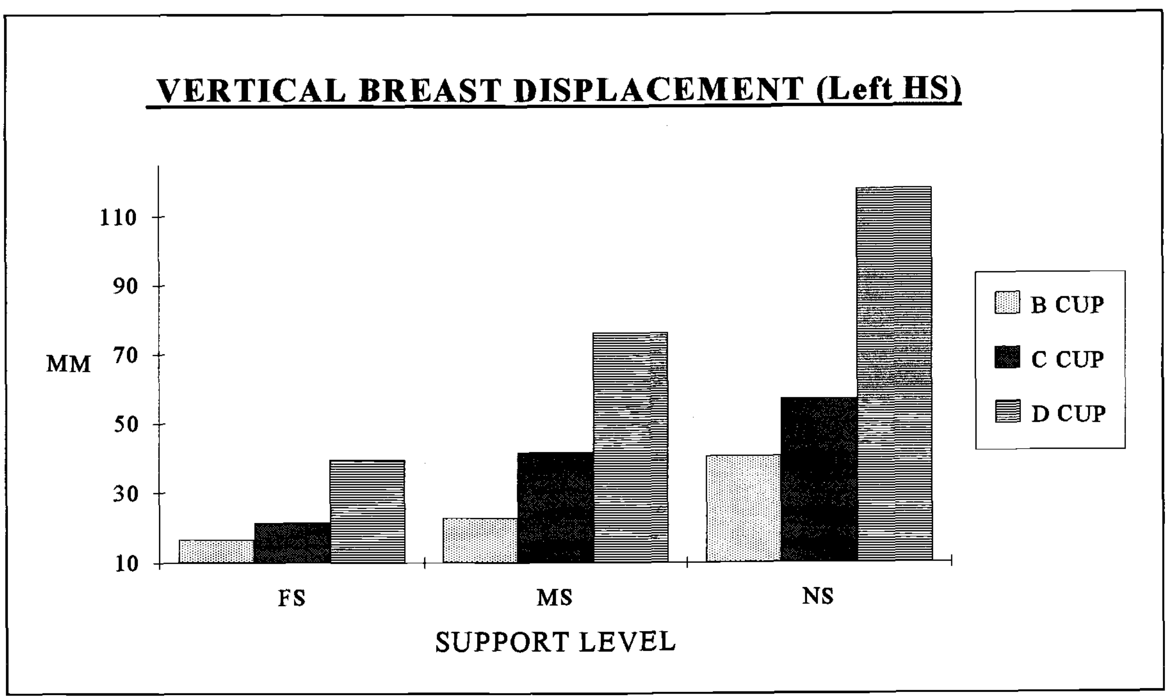

Figure 12: Mean Vertical Breast Displacement (Left HS)

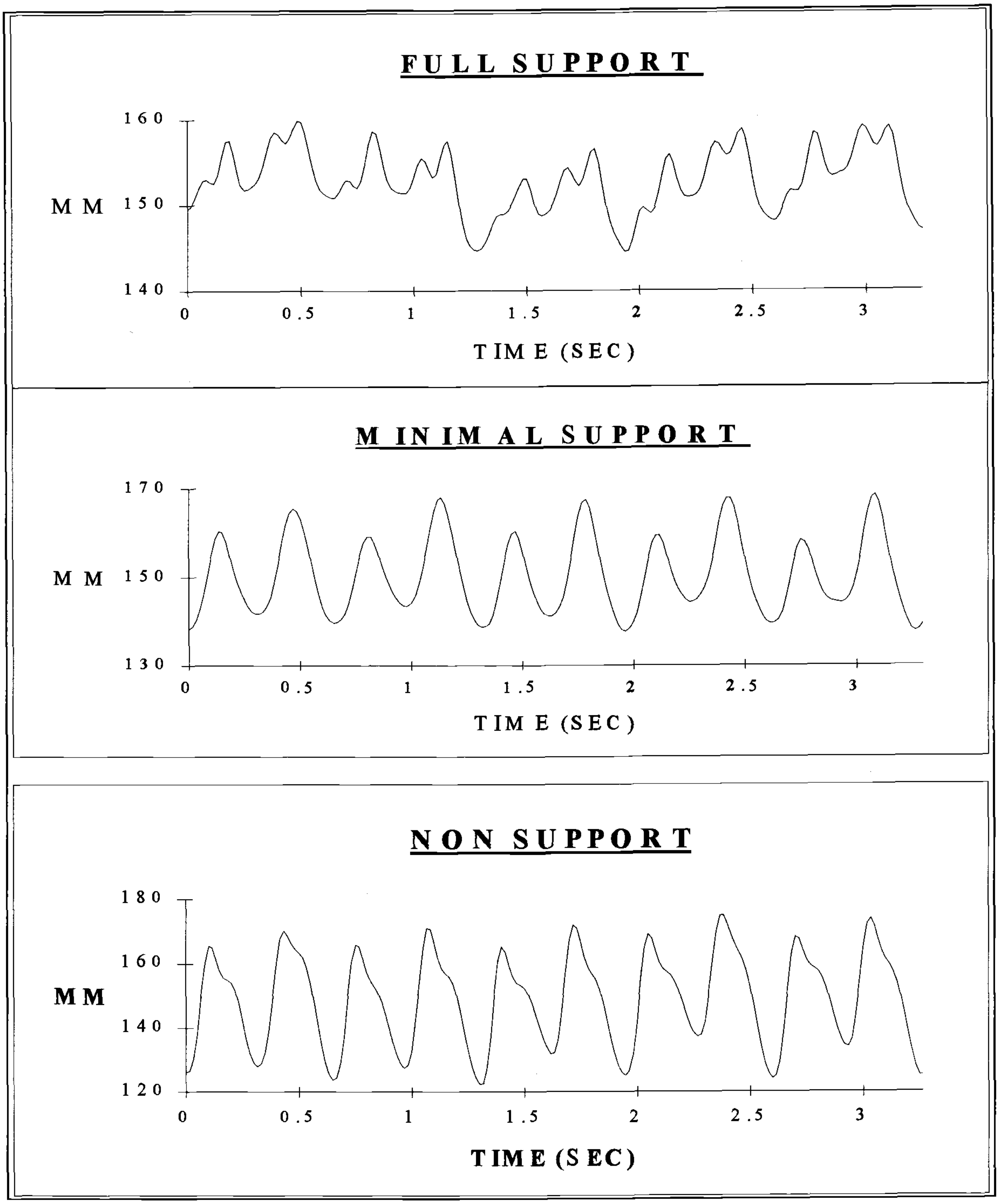

Figure 13: Vertical Breast Motion (Subject #4, B-Cup)

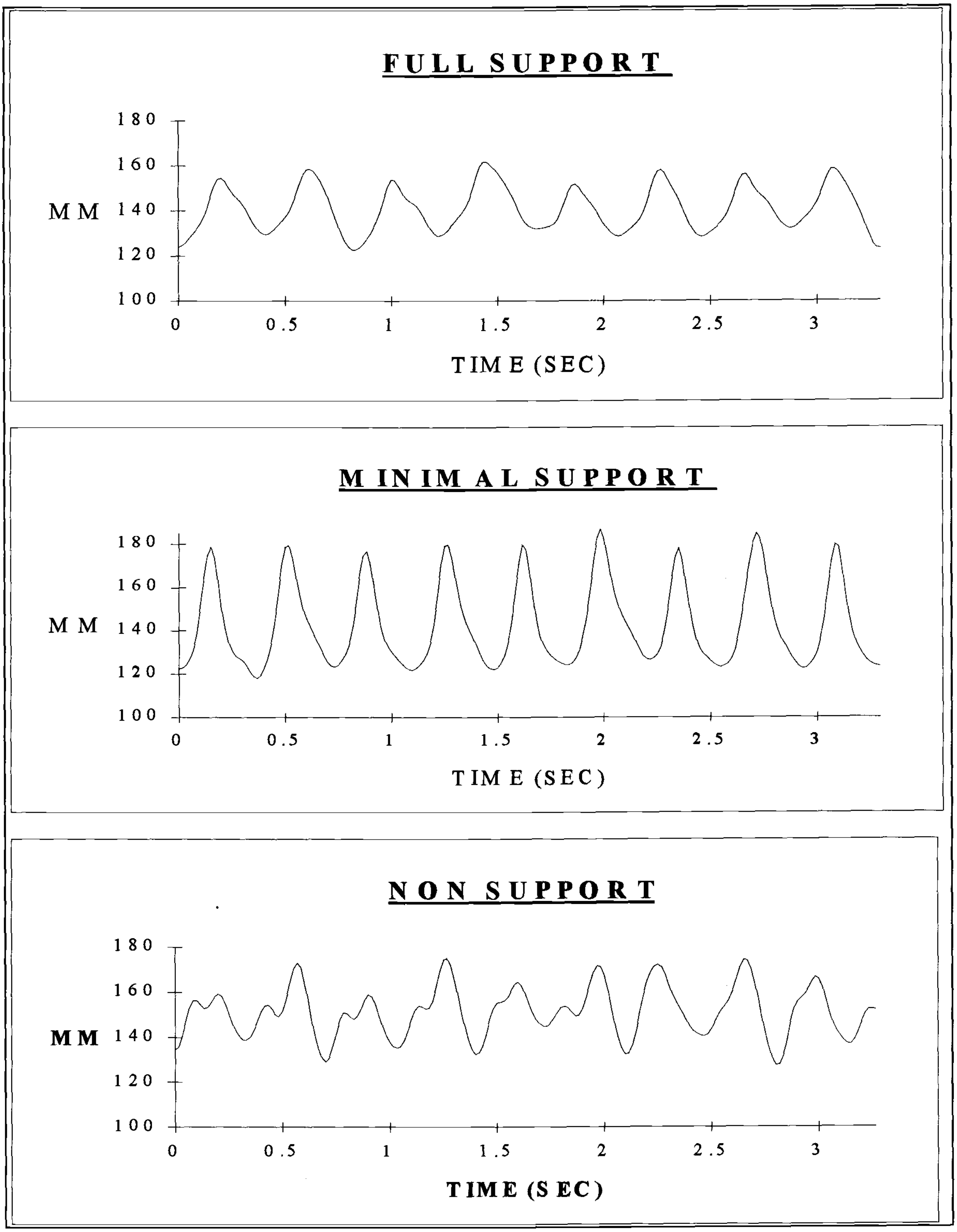

Figure 14: Vertical Breast Motion (Subject #6, C-Cup)

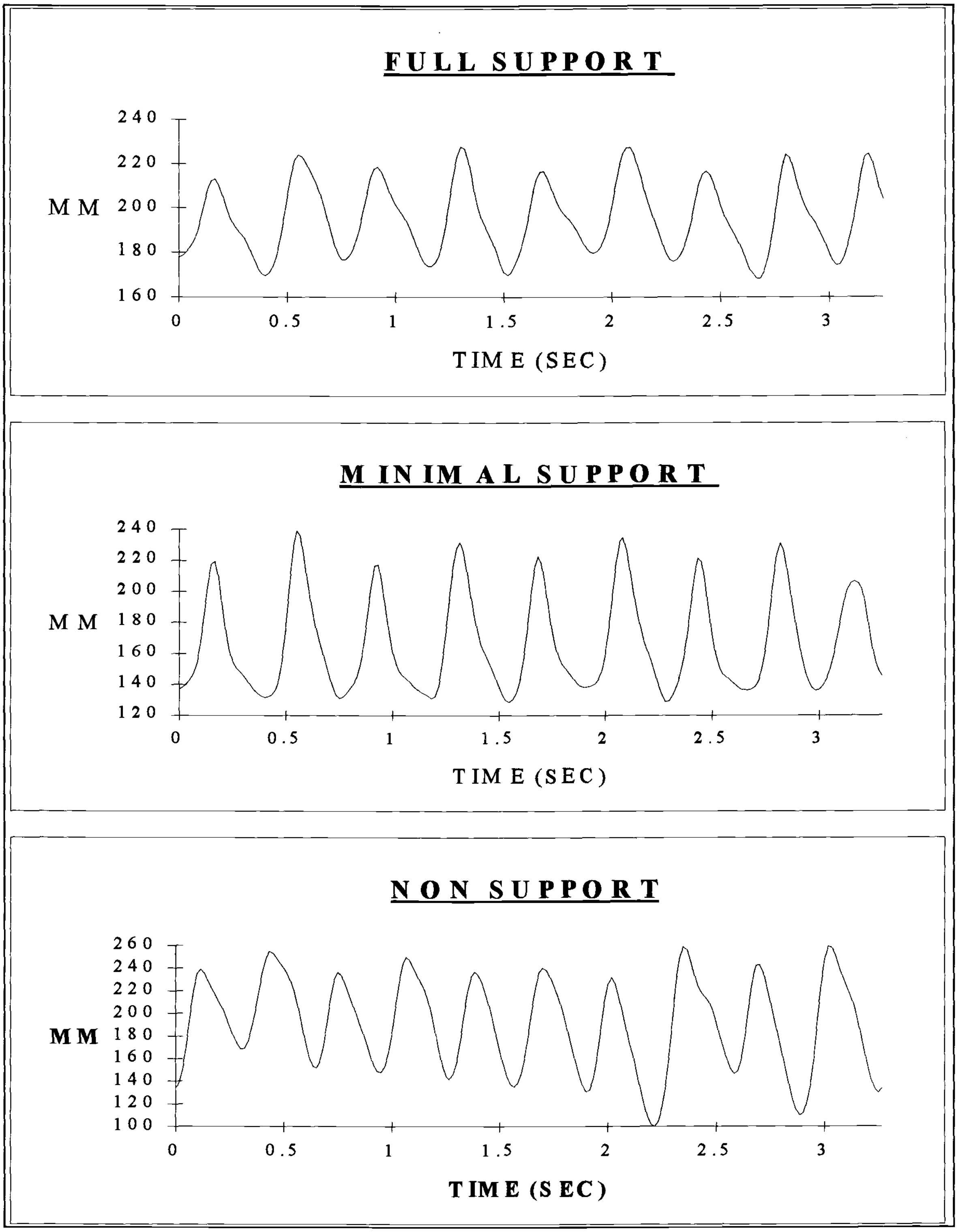

Figure 15: Vertical Breast Motion (Subject #15, D-Cup)

Subjective General Comfort Data

General comfort sensation (GCS) data were collected between minutes 4 and 5 of each support condition. All perceptions of discomfort increased as breast support decreased. The MS sports bra was perceived by the C and D cup subjects as being extremely non-supportive. Mean GCS across groups and support conditions was about 3.6. Mean GCS in the Full and Minimal Support conditions were not significantly different ($p = .17$). Mean GCS for each cup size group between the Full and Minimal Support conditions were significantly different for the B, C and D groups. (one tailed $p_B = .03$, $p_C = .0003$, and $p_D = .0002$). While the No Support condition was not included in the statistical comparison of means, it is worth noting that general comfort decreased as the support level decreased markedly in the larger size groups, (C and D). Table 11 summarizes the group and support level statistics for GCS.

Post Run General Comfort Sensation (GCS-P) data were collected after 5 minutes of rest between each support. Mean GCS-P across groups and support conditions was about 1.3. Mean GCS-P in the Full and Minimal Support conditions were not significantly different ($p = .62$). Mean GCS-P for each cup size group between the Full and Minimal Support conditions were significantly different for the C and D groups. (one tailed $p_B = .99$, $p_C = .009$. and $p_D = .009$). Table 12 summarizes the group and support level statistics for GCS-P.

Table 11: General Comfort Sensation During Run, Mean(SD)

SIZE GROUP	GCS FULL SUPPORT	MIN SUPPORT	NO SUPPORT	OVERALL
B	1.0(0)	2.4(1.2)	4.8(1.6)	2.7
C	1.0(0)	4.0(.63)	6.8(.4)	3.9
D	1.4(.8)	4.5(2.19)	6.4(.8)	4.1
OVERALL	1.1	3.6	6.1	3.6

Table 12: General Comfort Sensation Post Run, Mean(SD)

SIZE GROUP	GCS-P FULL SUPPORT	MIN SUPPORT	NO SUPPORT	OVERALL
B	1.0(0)	1.0(0)	1.4(.18)	1.1
C	1.0(0)	1.2(.4)	2.8(1.6)	1.7
D	1.0(0)	1.2(.4)	1.4(.8)	1.2
OVERALL	1.0	1.1	1.9	1.3

Discussion

Breast discomfort during physical activity is a common phenomenon for many large breasted active women. The purpose of this analysis was to determine the effects of breast support on movement patterns and comfort of the breasts during running.

Despite significant and substantial differences in general breast comfort and vertical breast motion, there was little change in movement pattern associated with the changes made in breast support. Stride Rate, Stride Length, Vertical Trunk Displacement, and Front Arm Angle ROM were relatively constant across full and minimal support conditions when analyzed comparing overall group averages. Thus, female runners in this study on average, apparently made little kinematic change in running technique to adjust to increased breast motion.

Previous studies (Gehlsen & Albohm, 1980; Haycock, Shierman & Gillette, 1978; Himmelsbach, Valiant, Lawson, & Eden, 1992; Lawson, 1985; Lawson, 1991; Lorentzen

& Lawson, 1987) have consistently demonstrated that vertical breast motion varies according to the support characteristics of the bra style worn, particularly as breast size increases (Lawson, 1985). All of these researchers indicated an association between excessive breast motion and discomfort and emphasized the need for substantial support. However, Lawson and Lorentzen (1990) found a significant correlation between perceived comfort and vertical breast motion for only one of eight bra styles evaluated. Perceived comfort scores were significantly affected by both cupsize of the subject and style of bra, but not by quantitative vertical displacement measurements. In this study, mean General Comfort Sensation scores for the whole group did not significantly decrease (indicating greater comfort) when a more supportive bra was worn, although there was a significant decrease of the larger (C and D) cupsize groups.

The findings of the present study, in accordance with those of Lawson and Lorentzen (1990), suggest that breast and bra comfort may be a broad perceptual concept of which vertical motion is only one component. It is possible that women may not be likely to adjust running kinematics in order to reduce breast motion if reduction of vertical breast displacement has only limited effect on the overall sense of breast comfort.

While this analysis compared mean values for each cup size group, some individual subjects changed substantially despite the group similarities. To illustrate this, figure 16 includes the VTD differences for three subjects (one from each cup size group). The B cup subject did not change VTD substantially between support levels, whereas the C and D cup subjects had apparently lower VTD as support decreased. A comparison of individual characteristics (Appendix C) shows that 9 of the 15 runners altered VTD in the this manner (decreased VTD with decreased support). This variable (VTD) was the only apparent individual change in running technique measured in this analysis. Differences in the kinematic variables (excluding vertical breast displacement) were small for most subjects. Future studies of this type would be improved by including individual comparisons, as it is evident that changes in breast support may influence individual subjects differently.

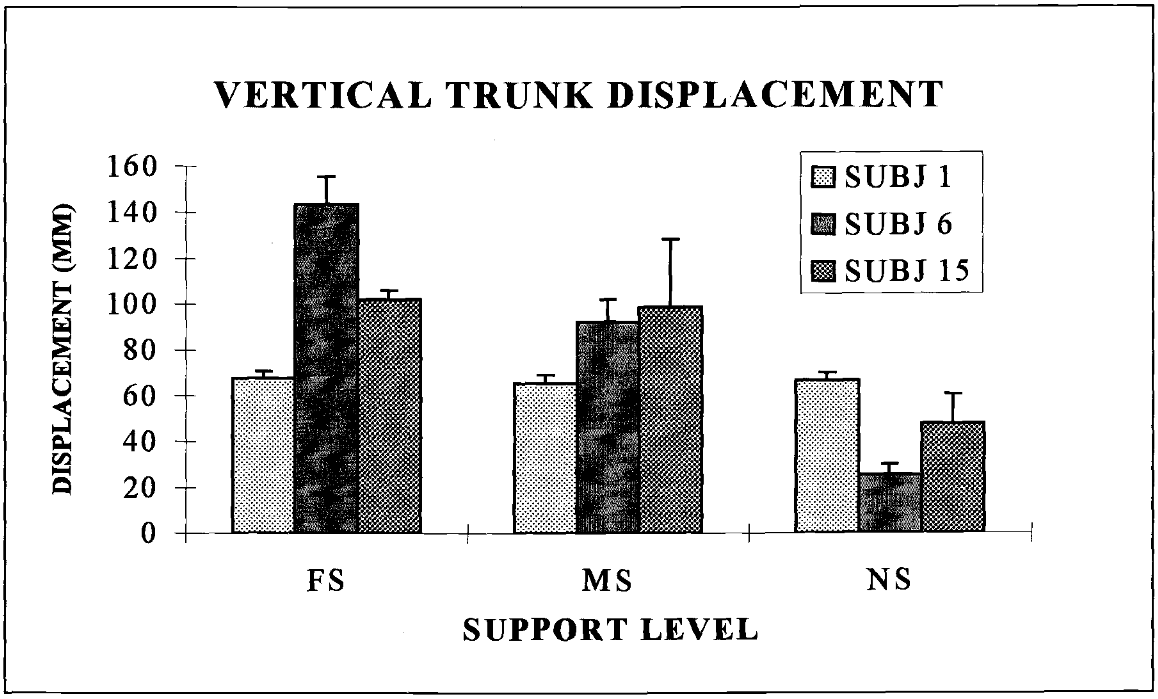

Figure 16: Individual VTD Kinematics

CHAPTER V
SUMMARY AND CONCLUSIONS

The primary purpose of this study was to determine the effects of breast support on biomechanical characteristics of females while running. In this analysis, two dimensional (2D) and three dimensional (3D) data were used throughout five consecutive running strides with three levels of breast support (full , minimal, and no-support). The 3D biomechanical variables included vertical and horizontal breast displacement, vertical trunk displacement, arm/trunk angle range of motion, and arm range of motion. Stride length, and stride rate were calculated from 2D video analysis. An additional purpose was to compare the subjective measure of general comfort sensation (GCS) between each level of breast support while running

Video collection was accomplished through the use of three video cameras. Two cameras filmed the torso of each runner for 3D analysis; one 2D camera filmed the side view of the runner's feet. A four point model was used in order to collect 3D coordinate data from the videotape. Each point was digitized at 30 frames per second. The same 5 strides from each camera's view were digitized. Three dimensional coordinates for the 4 points were calculated using the Motion Measurement System by Peak Performance Technologies Incorporated. Kinematic parameters were then calculated using the 3D and 2D data: Stride length, stride rate, vertical trunk displacement, vertical breast displacement [corresponding to the same-side (right) and opposite-side (left) heel strike independently], and horizontal breast displacement.

Comparison of the subjective measure of general comfort sensation, (GCS), between each level of breast support while running were made both during and after each breast support condition.

Relationships among variables were explored using individual t-tests for each cup size group between the full support (FS) and minimal support (MS) conditions, and one-way analysis of variance compared differences between breast size groups, with follow up pairwise differences investigated using Fisher's PLSD method.

Findings

The following are the major results of this study:

1. Stride length of the runners averaged 1.9 m and was not different across support conditions or breast size.

2. Stride Rate of the runners averaged 1.4 Hz and was not different across support conditions or breast size.

3. Vertical Trunk Displacement of the runners averaged 84 mm and was not different across support conditions or breast size.

4. Front Arm Angle Range of Motion of the runners averaged 16 degrees and was not different across support conditions or breast size.

5. Arm Angle Range of Motion of the runners averaged 42 degrees. Differences were found between breast size groups: The B and D size groups had slightly larger arm angles during the minimal support condition when it was compared to the full support condition, where the C cup size group had smaller arm angles when the two breast support conditions were compared. The absence of differences between the B and D cup size groups suggests that this measure may not have any practical significance.

6. Vertical Breast Displacement corresponding with the right heel strike (RVBD) of the runners averaged 54 mm overall. RVBD increased as breast support decreased. Differences were found between support conditions (B and D groups, and the C and D groups) and breast size groups.

7. Vertical Breast Displacement, corresponding with the left heel strike (LVBD) of the runners averaged 48 mm overall. LVBD increased as breast support decreased. Differences were found between support conditions (B and C groups, the B and D groups, and the C and D groups) and breast size groups.

8. Horizontal Breast Displacement (HBD) of the runners averaged 46 mm overall and was not different across support conditions or breast size.

9. General Comfort Sensation of the runners while running averaged 4 (uncomfortable) on a 7-point scale. All of the breast size groups showed increases in

discomfort between the full and minimal support conditions, however this difference did not exist across support conditions.

10. General Comfort Sensation post run (GCS-P) of the runners averaged 1 (comfortable) overall and was not different across support conditions or breast size.

Conclusions

Breast discomfort during physical activity is a common phenomenon for many large breasted active women. Limited research exists concerning the efficacy of sports bras to provide support for these women. Unlike previous investigations, this study included kinematic variables associated with running along with the typical variables describing breast support that have previously been described in sports bra studies. It was the purpose of this study to determine the effects of breast support on biomechanical and psychological characteristics of females while running. In this analysis the biomechanical variables included stride rate, stride length, trunk movement, and aspects of three dimensional breast and arm motion. The psychological measure evaluated perceived discomfort of the breast area during and after the run.

Analysis of vertical breast displacement over all subjects displayed a characteristic difference in breast motion. Vertical displacement appeared to be different for heelstrikes of the foot on the same side as the breast, than for heelstrikes of the contralateral foot, therefore these values were analyzed separately. Substantial increases in vertical displacement were found as breast support decreased. These increases extended across groups where the significant differences existed between the B & D groups and the C & D groups. LVBD comparisons displayed differences across all groups.

Perceived breast discomfort ratings increased as breast support decreased. This discomfort was substantially reduced after 5 minutes of rest for all subjects.

Despite substantial differences in general comfort sensation and breast motion between the 3 conditions of breast support, there were no changes in movement patterns associated with the changes in breast support for Stride Rate, Stride Length, Vertical

Trunk Movement and Front Arm Angle ROM. (The Arm Angle ROM decreased as breast support decreased for the C cup group only, a finding with little practical significance.

Implications and Recommendations

The findings in this study provide further insight towards the characteristics of female recreational runners. However they imply that running kinematics aren't affected by different levels of breast support. The large variability associated with the variables of vertical trunk displacement, and arm ranges of motion suggest some selectivity creating a more homogeneous groups would be helpful for future studies. While many of the subjects were recreational runners, however, the larger breast size groups (C and D) were not totally compiled of active runners. It would be of interest to find a larger, more uniform group to compare.

While it has been the goal of this study to further underline the effects of poor breast support during impact sports such as running, it is obvious that various factors have not been considered in this analysis. The way in which the arm angles were analyzed could possibly be modified by finding the average angle, or minimum arm angle throughout the running cycle, other than the change in angle between maximum and minimum. Possible follow up studies could include the control of stride length, stride rate, or teaching subjects to reduce vertical trunk displacement in order to minimize breast motion.

In this analysis, female runners on average, apparently make relatively little kinematic change in running technique to adjust to increased breast motion. However, some individual subjects changed substantially despite the group differences. Several subjects decreased their VTD substantially as breast support decreased. This variable appears to be the only substantial individual change in running technique that was measured in this analysis. Future recommendations may include some individual comparisons, as it is evident that changes in breast support influence subjects differently.

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APPENDICES

APPENDIX A
HUMAN SUBJECTS REVIEW

Breast Support for the Active Woman: Relationship to 3D Kinematics of Running

Significance:

Physical fitness is regarded by many epidemiologists as a means of reduction of the risks of coronary heart disease (CHD), hypertension, obesity, and osteoporosis. There are many motives that can reduce the adherence factors of participation. Some active, or "would-be-active" women are affected by large, sore, or tender breasts which can cause embarrassment and discomfort in activities where movement of the breasts occurs. Several questions arise from these observations: Are there changes in the way a woman moves as a result of breast discomfort, and does this have any effect on running performance? Can running performance be enhanced by use of a very supportive sports bra?

Methods:

All testing will be conducted in the Biomechanics Laboratory in the women's Building at OSU.

All subjects will report to the lab on 3 occasions for the following procedures:

DAY 1. Each subject will complete a medical questionnaire which will be utilized for the purpose of screening for cardiovascular disorders. The procedures of this study will be described, and the informed consent will be completed at this time. Estimation of body composition via skinfold calipers. This involves caliper placement on body fold in 3 sites to get an estimate of body composition. A treadmill accommodation run will also be conducted at this time to acquaint the runner with the feel of treadmill running. Each subject will perform three 10 minute runs, with a five minute break between runs.

DAY 2. Test day: Prior to the test, reflective adhesive markers will be placed on the sternum, above the right elbow, right shoulder, and right nipple. There will be 3 high speed video cameras recording running in three breast support conditions:

1). unsupported condition (unclothed from the waist up),

2). with a moderate support sports bra,

3). with a full support sports bra.

The test will involve a warm-up of 3 minutes of walking on the treadmill, and 5 minutes of running immediately following the warm-up. Subjects will be asked to describe their personal breast comfort from the GCS scale, (see following page).

Subjects:

Women experience breast discomfort while running either from excessive motion or pre-menstrual tenderness, and are likely to inhibit motion in order to reduce discomfort. This research will impose conditions of breast discomfort, in order to exemplify a representative group of sports bra users. Fifteen female volunteers will be selected on the basis of their physical characteristics (three groups of five according to breast cup size), training background (they have run habitually at least 10 miles per week for the previous three months or have been aerobically active and maintain the required 6 mph pace), and medical risk factors. The range of ages will be approximately 20 to 50 years.

Risks:

Participation by the subjects entails minor risks. The duration and intensity (6 mph) of each run will be low, and there will be adequate time allowed for familiarization of running on the treadmill. This diminishes the possibility of a serious health incident. There is a risk from minor skin irritation following removal of the retro-reflective adhesive body markers.

Benefits:

The results of this study will contribute to scientific study of women's sports equipment. Personally, each subject will acquire knowledge of personal body composition, and will receive a free sports bra as a result of participating in this study.

Anonymity of the Subjects:

The anonymity of each subject will be protected throughout the entire duration of the study. Only the consent forms of each subject will contain a subject's name. Other references to subjects will be numerical. During data collection, only the female researchers will be allowed within the data collection area contained in the Biomechanics Laboratory of the Women's Building at OSU. The video will remain with the primary researcher within a locked cabinet or briefcase. They will be viewed only by her during digitization processes. Any publication or discussion of the results will not contain any form of the subject's identity. After all data have been analyzed, the tapes will be erased.

Questionnaire and Testing Instruments used in this Study:

A general medical questionnaire will be utilized in order to screen possible subjects for coronary risk factors, (see following page). Persons wit a personal of family history or other predisposition to coronary disease will be excluded from participation. Positive answers of the following questions 1, 3, 4, 5, & 6 will disqualify the subject from participation.

The General Comfort Sensation scale will be described to each subject prior to treadmill accommodation and testing. The specific question asked will be "Thinking specifically of the breast area, which sensation most closely reflects your present breast comfort sensation?" The subject will indicate the number that most closely represents their comfort perception. The researcher will confirm the number indicated by reiterating the number selected.

GENERAL COMFORT SENSATION SCALE
1. Comfortable
2.
3. Slightly uncomfortable
4.
5. Uncomfortable
6.
7. Very uncomfortable

MEDICAL QUESTIONNAIRE

NAME ____________________________________

ADDRESS ____________________________________

PHONE ____________________

AGE ____________________

HEIGHT ____________________

WEIGHT ____________________

CIRCLE THE APPROPRIATE RESPONSE

1. Do you have a history of coronary artery disease, heart attack or stroke?
   Yes No

2. Do you smoke cigarettes?
   Yes No

3. If no, have you smoked cigarettes regularly in the last 5 years?
   Yes No

4. Have you ever been treated for diabetes mellitus?
   Yes No

5. Do you have high blood pressure (above 145/90)?
   Yes No

6. Do you have an elevated blood cholesterol (above 220 mg/dl)?
   Yes No Don't know

7. Did either of your parents or any of your siblings have a heart attack, bypass surgery, stroke, or diagnosis of coronary artery disease prior to age 55?
   Yes No If yes, age at which occurred______

INFORMED CONSENT FORM

TITLE: Breast Support for the Active Woman: Relationship to 3D Kinematics of Running

INVESTIGATORS: Anne L. Boschma, Gerald Smith; Assistant Professor, EXSS

PURPOSE: The purpose of this study is to compare the running kinematics (style) under three different breast support conditions, (unsupported, moderately supported, and superior supportive).

I have received an oral explanation of the study procedures and understand that they entail the following:

All testing will be conducted in the Biomechanics Laboratory in the Women's Building at OSU. As a subject I will report to the lab on 2 occasions for the following procedures:

DAY 1. Estimation of body composition via skinfold calipers.
Treadmill accommodation run. This requires me to perform three sets of 10 minute runs in order to become familiarized with treadmill running.

DAY 2. Biomechanical, and psychological data collection. Prior to and during the test, reflective adhesive markers will be placed on reference points of my body. There will be 3 high speed video cameras recording my running in each breast support condition. The test involves a warm-up of 3 minutes of walking on the treadmill, and 5 minutes of running at a 10 min. mile pace immediately following the warm-up. I will be asked to describe my personal breast comfort from the GCS scale. This test will be run in each of the three breast support conditions: 1). an unsupported condition (unclothed from the waist up), 2). with a moderate support sports bra, and 3). with a full support sports bra.

I accept that my participation includes minimal risk. The test involves running at a low intensity and duration. There is a risk from skin irritation following removal of the retro-reflective adhesive body markers.

I understand that the results will be confidential and I will not be identified in the presentation or publication in any way. I understand that the laboratory area will be highly secured and only accessible to the female researchers during each test session. The video films will be secured and locked until relevant data is withdrawn, after which the tapes will be erased.

The benefits of my participation include the contribution to scientific study of sports equipment, knowledge gained of my personal body composition, and a free sports bra.

I understand that my participation involves 2 visits within a time frame of two weeks, with each visit requiring 60 minutes of my time.

I have been completely informed of and understand the nature of this research.

The researchers have offered to answer any further questions I may have.

I understand that my participation is completely voluntary and I may withdraw at any time without prejudice, or loss of benefits to which my participation entitles me.

If any question arise at any time during my participation I am to call Anne Boschma, at 737-5933.

I have read the foregoing and agree to participate in this study.

Subject's Signature	Date
Subject's address	
Investigator's Signature	Date

APPENDIX B

STATISTICAL TABLES

Table 13: Anova Table for Stride Length
FS-MS measured in meters

	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE	P-VALUE
SIZE	2	.017	.009	1.832	0.20
RESIDUAL	12	.056	.005		

Table 14: Means Table for Stride Length
FS-MS measured in meters

	COUNT	MEAN	STD. DEV.	STD. ERR.
B	5	-0.043	0.069	0.031
C	5	0.039	0.094	0.042
D	5	0.004	0.024	0.011

Table 15: t - Statistics for Stride Length
FS-MS measured in meters

	VARIANCE (pooled)	T - STATISTIC	P - VALUE
B	0.0307	-1.399	0.91
C	0.0307	1.269	0.11
D	0.0307	0.108	0.46

Table 16: Fisher's PLSD for Stride Length
FS-MS measured in meters

	MEAN DIFF	CRIT DIFF	P - VALUE
B, C	-.083	0.094	0.08
B, D	-0.047	0.094	0.30
C, D	0.36	0.094	0.43

* denotes significance @ p < .05

Table 17: Anova Table for Stride Rate
FS-MS measured in Hz

	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE	P-VALUE
SIZE	2	.010	.005	2.024	.17
RESIDUAL	12	.028	.002		

Table 18: Means Table for Stride Rate
FS-MS measured in Hz

	COUNT	MEAN	STD. DEV.	STD. ERR.
B	5	0.036	0.059	0.026
C	5	-0.025	0.059	0.026
D	5	-0.002	0.014	0.006

Table 19: t - Statistics for Stride Rate
FS-MS measured in Hz

	VARIANCE (pooled)	T - STATISTIC	P - VALUE
B	0.0218	1.648	0.94
C	0.0218	-1.145	0.14
D	0.0218	-0.092	0.46

Table 20: Fisher's PLSD for Stride Rate
FS-MS measured in Hz

	MEAN DIFF	CRIT DIFF	P - VALUE
B, C	0.061	0.067	0.07
B, D	0.037	0.067	0.25
C, D	-0.024	0.067	0.45

* denotes significance @ p < .05

Table 21: Anova Table for Vertical Trunk Displacement
FS-MS measured in mm

	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE	P-VALUE
SIZE	2	1157.702	578.851	1.669	0.23
RESIDUAL	12	4162.435	346.870		

Table 22: Means Table for Vertical Trunk Displacement
FS-MS measured in mm

	COUNT	MEAN	STD. DEV.	STD. ERR.
B	5	-12.071	19.914	8.906
C	5	8.942	25.288	11.309
D	5	2.453	2.139	0.957

Table 23: t - Statistics for Vertical Trunk Displacement
FS-MS measured in mm

	VARIANCE (pooled)	T - STATISTIC	P - VALUE
B	8.3292	-1.449	0.91
C	8.3292	1.074	0.15
D	8.3292	0.295	0.39

Table 24: Fisher's PLSD for Vertical Trunk Displacement
FS-MS measured in mm

	MEAN DIFF	CRIT DIFF	P - VALUE
B, C	-21.013	25.665	0.10
B, D	-14.524	25.665	0.24
C, D	6.489	25.665	0.59

* denotes significance @ $p < .05$

Table 25: Anova Table for Front Arm Angle Range of Motion
FS-MS measured in degrees

	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE	P-VALUE
SIZE	2	63.631	31.816	1.249	0.32
RESIDUAL	12	305.663	25.472		

Table 26: Means Table for Front Arm Angle Range of Motion
FS-MS measured in degrees

	COUNT	MEAN	STD. DEV.	STD. ERR.
B	5	1.107	3.104	1.388
C	5	-2.388	4.094	1.831
D	5	-3.791	7.703	3.163

Table 27: t - Statistics for Front Arm Angle Range of Motion
FS-MS measured in degrees

	VARIANCE (pooled)	T - STATISTIC	P - VALUE
B	2.3907	0.463	.33
C	2.3907	-0.999	.67
D	2.3907	-.1586	.93

Table 28: Fisher's PLSD for Front Arm Angle Range of Motion
FS-MS measured in degrees

	MEAN DIFF	CRIT DIFF	P - VALUE
B, C	3.496	6.955	0.30
B, D	4.898	6.955	0.15
C, D	1.403	6.955	0.67

* denotes significance @ $p < .05$

Table 29: Anova Table for Arm Angle Range of Motion
FS-MS measured in degrees

	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE	P-VALUE
SIZE	2	394.998	197.499	6.403	0.01 *
RESIDUAL	12	370.147	30.846		

Table 30: Means Table for Arm Angle Range of Motion
FS-MS measured in degrees

	COUNT	MEAN	STD. DEV.	STD. ERR.
B	5	-3.038	2.965	1.326
C	5	8.354	5.129	2.294
D	5	-1.943	7.579	3.390

Table 31: t - Statistics for Arm Angle Range of Motion
FS-MS measured in degrees

	VARIANCE (pooled)	T - STATISTIC	P - VALUE
B	2.1012	-1.446	0.91
C	2.1012	3.976	0.0009 *
D	2.1012	-0.925	0.81

Table 32: Fisher's PLSD for Arm Angle Range of Motion
FS-MS measured in degrees

	MEAN DIFF	CRIT DIFF	P - VALUE
B, C	-11.392	7.653	0.007 *
B, D	-1.095	7.653	0.76
C, D	10.297	7.653	0.01 *

* denotes significance @ $p < .05$

Table 33: Anova Table for Horizontal Breast Displacement
FS-MS measured in meters

	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE	P-VALUE
SIZE	2	2.247	1.124	.017	.98
RESIDUAL	12	810.395	67.533		

Table 34: Means Table for Horizontal Breast Displacement
FS-MS measured in meters

	COUNT	MEAN	STD. DEV.	STD. ERR.
B	5	-2.933	9.661	4.321
C	5	-3.078	7.117	3.183
D	5	-2.194	7.656	3.424

Table 35: t - Statistics for Horizontal Breast Displacement
FS-MS measured in meters

	VARIANCE (pooled)	T - STATISTIC	P - VALUE
B	3.6752	-0.798	-0.22
C	3.6752	-0.8385	-0.21
D	3.6752	-0.597	-0.28

Table 36: Fisher's PLSD for Horizontal Breast Displacement
FS-MS measured in meters

	MEAN DIFF	CRIT DIFF	P - VALUE
B, C	0.145	11.324	0.99
B, D	-0.739	11.324	0.89
C, D	-0.884	11.324	0.87

* denotes significance @ $p < .05$

Table 37: Anova Table for Vertical Breast Displacement at Right Heel Strike
FS-MS measured in mm

	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE	P-VALUE
SIZE	2	2298.007	1149.004	13.340	.0009 *
RESIDUAL	12	1033.589	86.132		

Table 38: Means Table for Vertical Breast Displacement at Right Heel Strike
FS-MS measured in mm

	COUNT	MEAN	STD. DEV.	STD. ERR.
B	5	-9.429	6.494	2.904
C	5	-20.412	7.481	3.346
D	5	-39.393	12.659	5.661

Table 39: t - Statistics for Vertical Breast Displacement at Right Heel Strike
FS-MS measured in mm

	VARIANCE (pooled)	T - STATISTIC	P - VALUE
B	4.1504	-2.272	0.02 *
C	4.1504	-4.918	0.0001 *
D	4.1504	-9.491	< 0.0001 *

Table 40: Fisher's PLSD for Vertical Breast Displacement at Right Heel Strike
FS-MS measured in mm

	MEAN DIFF	CRIT DIFF	P - VALUE
B, C	10.984	12.789	0.09
B, D	29.965	12.789	0.0003 *
C, D	18.981	12.789	0.007 *

* denotes significance @ p < .05

Table 41: Anova Table for Vertical Breast Displacement at Left Heel Strike
FS-MS measured in mm

	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE	P-VALUE
SIZE	2	2352.220	1176.110	23.945	< 0.0001 *
RESIDUAL	12	589.397	49.116		

Table 42: Means Table for Vertical Breast Displacement at Left Heel Strike
FS-MS measured in mm

	COUNT	MEAN	STD. DEV.	STD. ERR.
B	5	-6.066	5.144	2.300
C	5	-19.952	8.445	3.777
D	5	-36.695	7.040	3.149

Table 43: t - Statistics for Vertical Breast Displacement at Left Heel Strike
FS-MS measured in mm

	VARIANCE (pooled)	T - STATISTIC	P - VALUE
B	3.1341	-1.935	-.04 *
C	3.1341	-6.366	< -0.0001 *
D	3.1341	-11.708	< -0.0001 *

Table 44: Fisher's PLSD for Vertical Breast Displacement at Left Heel Strike
FS-MS measured in mm

	MEAN DIFF	CRIT DIFF	P - VALUE
B, C	13.886	9.657	0.009 *
B, D	30.629	9.657	< 0.0001 *
C, D	16.744	9.657	0.002 *

* denotes significance @ p < .05

Table 45: Anova Table for General Comfort Sensation
FS-MS measured during run

	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE	P-VALUE
SIZE	2	9.100	4.550	2.068	0.17
RESIDUAL	12	26.400	2.200		

Table 46: Means Table for General Comfort Sensation
FS-MS measured during run

	COUNT	MEAN	STD. DEV.	STD. ERR.
B	5	1.400	1.342	0.600
C	5	3.000	0.707	0.316
D	5	3.100	2.074	0.927

Table 47: t - Statistics for General Comfort Sensation
FS-MS measured during run

	VARIANCE (pooled)	T - STATISTIC	P - VALUE
B	0.6634	2.100	0.03 *
C	0.6634	4.522	0.0003 *
D	0.6634	4.673	0.0002 *

Table 48: Fisher's PLSD for General Comfort Sensation
FS-MS measured during run

	MEAN DIFF	CRIT DIFF	P - VALUE
B, C	-1.600	2.044	0.11
B, D	-1.700	2.044	0.10
C, D	-0.100	2.044	0.92

* denotes significance @ $p < .05$

Table 49: Anova Table for General Comfort Sensation--Post Test .
FS-MS measured 5 minutes after run

	DF	SUM OF SQUARES	MEAN SQUARE	F-VALUE	P-VALUE
SIZE	2	0.133	0.067	0.500	0.62
RESIDUAL	12	1.600	0.133		

Table 50: Means Table for General Comfort Sensation--Post Test
FS-MS measured 5 minutes after run

	COUNT	MEAN	STD. DEV.	STD. ERR.
B	5	0.000	0.000	0.000
C	5	0.200	0.447	0.200
D	5	0.200	0.447	0.200

Table 51: t - Statistics for General Comfort Sensation--Post Test
FS-MS measured 5 minutes after run

	VARIANCE (pooled)	T - STATISTIC	P - VALUE
B	0.1632	0.000	--
C	0.1632	2.739	0.009 *
D	0.1632	2.739	0.009 *

Table 52: Fisher's PLSD for General Comfort Sensation--Post Test
FS-MS measured 5 minutes after run

	MEAN DIFF	CRIT DIFF	P - VALUE
B, C	-0.200	0.503	0.40
B, D	-0.200	0.503	0.40
C, D	0.000	0.503	--

* denotes significance @ $p < .05$

APPENDIX C

INDIVIDUAL KINEMATIC DATA

Mean(SD) of Five Strides

Table 53: **Individual Data for Stride Length & Stride Rate**

SUBJECT	STRIDE LENGTH (m) (SL)			STRIDE RATE (Hz) (SR)		
(SIZE)	FS	MS	NS	FS	MS	NS
1 (B)	1.699(.00)	1.859(.04)	1.859(.00)	1.579(.00)	1.442(.04)	1.442(.00)
2 (B)	2.020(.04)	2.039(.00)	2.020(.04)	1.327(.03)	1.315(.00)	1.327(.03)
3 (B)	1.895(.00)	1.877(.04)	1.895(.05)	1.415(.00)	1.429(.03)	1.415(.04)
4 (B)	1.752(.00)	1.789(.04)	1.789(.00)	1.530(.00)	1.499(.04)	1.499(.00)
5 (B)	1.966(.04)	1.984(.05)	1.895(.00)	1.364(.03)	1.352(.03)	1.415(.00)
6 (C)	2.198(.07)	2.002(.05)	1.895(.05)	1.220(.04)	1.339(.03)	1.415(.04)
7 (C)	1.734(.05)	1.697(.00)	1.574(.05)	1.547(.04)	1.580(.00)	1.704(.05)
8 (C)	1.930(.04)	1.984(.05)	1.966(.04)	1.389(.03)	1.352(.03)	1.364(.03)
9 (C)	1.789(.00)	1.788(.04)	1.789(.08)	1.499(.00)	1.500(.03)	1.499(.06)
10 (C)	2.056(.04)	2.039(.04)	2.002(.05)	1.304(.03)	1.315(.03)	1.339(.03)
11 (D)	1.824(.04)	1.824(.05)	1.806(.08)	1.470(.03)	1.470(.04)	1.485(.06)
12 (D)	2.270(.04)	2.289(.05)	2.360(.00)	1.181(.02)	1.172(.03)	1.136(.00)
13 (D)	1.859(.04)	1.877(.00)	1.680(.08)	1.442(.03)	1.429(.00)	1.596(.07)
14 (D)	2.270(.04)	2.234(.04)	2.163(.05)	1.181(.03)	1.200(.03)	1.240(.03)
15 (D)	2.020(.04)	2.002(.00)	1.698(.08)	1.327(.03)	1.339(.00)	1.579(.07)

Table 54: **Individual Data for Front Arm Angle ROM & Arm Angle ROM**

SUBJECT	FRONT ARM ANGLE ROM (DEGREES) (FA ROM)			ARM ANGLE ROM (DEGREES) (A ROM)		
(SIZE)	FS	MS	NS	FS	MS	NS
1 (B)	15.5(1.4)	18.9(3.4)	20.1(3.9)	26.2(1.9)	28.6(1.4)	28.3(3.8)
2 (B)	12.4(1.2)	11.8(1.2)	10.6(4.9)	48.6(1.3)	47.3(0.7)	46.5(1.3)
3 (B)	19.9(3.5)	16.0(5.6)	12.2(3.0)	43.8(3.5)	49.9(1.3)	52.9(4.0)
4 (B)	15.9(2.6)	11.7(0.9)	11.6(3.3)	26.7(1.3)	32.3(1.7)	37.2(0.0)
5 (B)	9.3(1.8)	8.9(2.7)	10.0(2.2)	41.7(1.3)	44.1(2.1)	41.4(1.1)
6 (C)	10.0(2.9)	10.3(1.4)	20.2(3.4)	51.2(1.4)	41.2(3.6)	23.3(2.6)
7 (C)	13.3(1.9)	18.0(2.9)	8.5(1.5)	47.4(5.6)	39.8(3.4)	32.7(1.9)
8 (C)	18.0(1.5)	21.7(3.1)	18.4(2.5)	34.4(5.6)	31.3(0.9)	31.2(2.0)
9 (C)	18.1(4.1)	14.5(1.4)	9.9(3.6)	44.3(5.1)	39.4(0.8)	40.6(2.2)
10 (C)	11.8(1.6)	18.6(2.9)	17.3(3.8)	49.4(3.0)	33.2(2.0)	47.7(6.6)
11 (D)	12.1(1.9)	16.4(1.4)	11.8(1.9)	39.9(2.5)	35.7(1.9)	34.2(3.1)
12 (D)	20.3(1.7)	16.0(2.3)	21.4(5.9)	53.4(3.1)	65.4(2.7)	76.2(4.3)
13 (D)	15.1(2.1)	18.3(2.6)	12.9(1.8)	52.1(1.9)	46.0(2.3)	29.1(4.0)
14 (D)	27.3(5.6)	28.2(1.6)	31.0(2.8)	58.7(0.8)	59.6(1.6)	61.8(1.7)
15 (D)	14.7(2.8)	29.7(3.6)	11.5(3.9)	38.2(2.0)	45.4(1.9)	37.7(4.8)

Table 55: **Individual Data for Horizontal Breast Displacement & Vertical Trunk Displacement**

SUBJECT	HORIZONTAL BREAST DISPLACEMENT (mm) (HBD)			VERTICAL TRUNK DISPLACEMENT (mm) (VTD)		
(SIZE)	FS	MS	NS	FS	MS	NS
1 (B)	13.9(1.4)	16.7(1.4)	31.0(1.5)	67.5(3.2)	65.3(3.5)	66.3(3.5)
2 (B)	21.3(2.9)	23.6(2.1)	29.5(1.1)	98.6(5.1)	102.63.9()	82.2(6.7)
3 (B)	41.8(3.1)	55.5(5.5)	62.9(3.8)	66.0(4.3)	79.3(4.1)	74.9(5.2)
4 (B)	25.7(1.0)	13.4(1.1)	19.8(3.9)	28.9(4.8)	74.9(4.8)	72.7(6.8)
5 (B)	29.3(2.4)	37.4(2.8)	49.6(3.9)	95.4(6.2)	94.6(4.4)	73.1(4.3)
6 (C)	25.3(1.5)	22.9(3.2)	61.4(4.3)	143.4(12.2)	92.2(9.9)	25.6(4.3)
7 (C)	38.2(4.8)	41.8(3.6)	57.0(2.0)	66.4(9.5)	63.5(8.5)	41.9(9.8)
8 (C)	34.3(3.7)	28.5(1.9)	46.4(0.6)	66.1(3.9)	83.3(6.0)	68.8(9.4)
9 (C)	27.5(3.1)	37.1(3.8)	98.9(6.3)	69.5(4.3)	66.7(3.5)	56.3(6.0)
10 (C)	15.4(2.2)	25.7(1.9)	30.6(2.5)	108.0(7.6)	103.1(7.2)	91.7(7.8)
11 (D)	38.1(4.7)	33.5(5.1)	95.7(4.3)	95.2(7.5)	93.5(10.2)	66.0(8.7)
12 (D)	46.7(2.4)	47.2(4.9)	98.6(9.3)	117.5(14.8)	113.3(8.4)	102.1(8.7)
13 (D)	54.7(3.9)	69.6(1.6)	94.9(3.6)	89.2(7.9)	90.2(7.0)	39.8(2.9)
14 (D)	36.1(3.1)	39.0(2.8)	95.1(3.4)	151.7(11.1)	147.8(13.1)	127.1(8.7)
15 (D)	76.5(2.7)	73.8(1.2)	89.2(11.4)	101.9(4.0)	98.5(29.7)	47.5(13.1)

Table 56: **Individual Data for Vertical Breast Displacement at Right and Left Heel Strikes**

SUBJECT	VERTICAL BREAST DISPLACEMENT AT RIGHT HEEL STRIKE (mm) (RVBD)			VERTICAL BREAST DISPLACEMENT AT LEFT HEEL STRIKE (mm) (LVBD)		
(SIZE)	FS	MS	NS	FS	MS	NS
1 (B)	9.4(0.9)	13.8(1.2)	36.3(2.6)	6.2(1.3)	9.5(1.4)	33.9(1.4)
2 (B)	27.1(0.6)	28.5(1.5)	41.4(2.6)	13.8(1.8)	17.8(0.9)	37.1(2.1)
3 (B)	21.9(2.0)	36.6(1.8)	39.3(3.0)	21.4(2.7)	32.7(2.7)	43.8(3.8)
4 (B)	8.0(1.3)	24.5(1.0)	40.2(2.3)	9.1(1.4)	20.7(1.3)	42.5(1.8)
5 (B)	36.9(2.9)	47.2(2.2)	53.8(1.3)	33.1(2.5)	33.2(1.6)	45.2(1.3)
6 (C)	30.2(2.7)	60.2(2.0)	34.3(4.4)	26.7(4.2)	55.2(2.4)	33.0(5.8)
7 (C)	21.9(1.5)	46.0(3.1)	44.9(1.4)	19.3(1.7)	48.8(2.2)	44.2(2.9)
8 (C)	20.5(2.7)	40.7(6.3)	48.3(3.9)	21.6(5.3)	34.3(2.2)	59.7(4.2)
9 (C)	38.6(2.8)	48.5(3.0)	104.9(5.3)	24.5(3.0)	40.9(0.7)	87.6(5.2)
10 (C)	19.7(2.4)	37.6(2.2)	58.8(2.9)	15.8(5.2)	28.4(2.9)	60.5(2.3)
11 (D)	57.8(2.7)	90.5(4.2)	128.6(3.4)	45.5(5.3)	80.9(4.4)	141.5(4.1)
12 (D)	59.0(5.4)	81.2(3.3)	113.4(3.6)	45.5(2.9)	71.7(3.3)	128.4(8.6)
13 (D)	49.5(1.7)	102.7(5.3)	109.2(2.1)	39.8(6.7)	75.4(31.5)	102.1(6.3)
14 (D)	41.4(1.6)	80.3(0.9)	128.5(1.2)	24.4(1.1)	68.6(1.1)	121.2(12.9)
15 (D)	49.6(7.0)	99.5(4.3)	113.7(24.5)	42.9(5.1)	85.0(8.4)	96.4(6.8)

APPENDIX D

INDIVIDUAL GENERAL COMFORT DATA

Table 57: **Individual Data for General Comfort Sensation During and After Run**

SUBJECT	GENERAL COMFORT SENSATION (GCS)			GENERAL COMFORT SENSATION (GCS POST RUN)		
(SIZE)	FS	MS	NS	FS	MS	NS
1 (B)	1	3	5	1	1	3
2 (B)	1	1	3	1	1	1
3 (B)	1	1	3	1	1	1
4 (B)	1	3	7	1	1	1
5 (B)	1	4	6	1	1	1
6 (C)	1	3	7	1	1	3
7 (C)	1	4	6	1	1	1
8 (C)	1	4	7	1	1	4
9 (C)	1	4	7	1	1	1
10 (C)	1	5	7	1	2	5
11 (D)	1	3	5	1	1	1
12 (D)	3	7	7+	1	2	3
13 (D)	1	6	7	1	1	1
14 (D)	1	1	6	1	1	1
15 (D)	1	5.5	7+	1	1	1

APPENDIX E

INDIVIDUAL ANTHROPOMETRIC DATA

Table 58: **Individual Anthropometric Data**

SUBJECT (SIZE)	AGE (YR.)	HEIGHT (M)	WEIGHT (KG)	BODY FAT %	RECREATION
1 (B)	43	1.74	63.18	13.9	9 mi/wk
2 (B)	23	1.70	66.36	18.0	15 mi/wk
3 (B)	34	1.73	57.72	25.0	bike/run/swim
4 (B)	41	1.65	52.27	20.9	25 mi/wk
5 (B)	28	1.70	80.92	34.1	20 mi/wk
6 (C)	36	1.68	62.73	23.0	aerobics 2x/wk
7 (C)	58	1.65	68.18	26.4	12 mi/wk
8 (C)	37	1.63	56.91	26.3	6-7 mi/wk
9 (C)	28	1.68	70.00	25.8	10-25 mi/wk
10 (C)	28	1.70	60.00	16.5	12-15 mi/wk
11 (D)	22	1.70	58.18	17.8	20-25 mi/wk
12 (D)	33	1.63	84.09	33.3	aerobics/swim
13 (D)	21	1.75	79.55	29.5	9 mi/wk
14 (D)	21	1.73	61.36	15.6	12 mi/wk
15 (D)	19	1.69	75.00	25.8	6 mi/wk

APPENDIX F

DIRECT LINEAR TRANSFORMATION

Table 59: **Control Structure Coordinates for Subject 1**

CONTROL STRUCTURE COORDINATES (mm) SUBJECT # 1			
POINT	X	Y	Z
C	263.008	259.221	172.682
E	-3.446	1022.638	-1.057
F	255.244	763.372	170.743
H	1024.354	1019.126	2.076
I	765.774	767.261	170.198
L	762.068	255.070	166.438
O	764.484	255.069	511.890
Q	1020.509	1022.330	679.527
R	767.993	768.859	512.226
T	3.353	1020.018	680.954
U	252.828	766.759	510.116
X	253.899	253.485	510.772

Table 60: **Reprediction Errors for Subject 1**

REPREDICTION ERRORS (mm) SUBJECT # 1				
POINT	X	Y	Z	RESULTANT
C	7.008	3.221	2.082	7.989
E	-3.446	1.038	-1.057	3.751
F	-0.756	-2.328	0.143	2.451
H	2.754	-2.474	2.076	4.245
I	0.074	1.561	-0.402	1.613
L	-3.632	-0.930	-4.162	5.602
O	-1.216	-0.931	1.390	2.068
Q	-1.091	0.730	-1.573	2.048
R	2.293	3.159	1.726	4.268
T	3.353	-1.582	-0.146	3.710
U	-3.172	1.059	-0.384	3.366
X	-2.101	-2.515	0.272	3.288
AVERAGE MEAN SQUARE ERROR	**3.247**	**2.081**	**1.781**	**4.248**

Table 61: **Control Structure Coordinates For Subjects 4 & 6**

CONTROL STRUCTURE COORDINATES (mm) SUBJECTS # 4 & 6			
POINT	X	Y	Z
C	259.795	259.824	172.502
E	-2.189	1023.382	-1.995
F	256.930	763.261	172.896
H	1023.935	1020.521	2.532
I	762.822	765.297	170.201
L	764.297	254.106	166.084
O	768.134	256.711	512.173
Q	1020.099	1022.873	681.248
R	766.173	767.649	508.487
T	1.851	1020.635	680.971
U	257.455	765.133	509.384
X	250.729	253.853	512.070

Table 62: **Reprediction Errors for Subjects 4 & 6**

REPREDICTION ERRORS (mm) SUBJECTS # 4 & 6				
POINT	X	Y	Z	RESULTANT
C	3.795	3.824	1.9902	5.714
E	-2.189	1.782	-1.995	3.456
F	0.930	-2.439	2.296	3.476
H	2.335	-1.079	2.532	3.609
I	-2.878	-0.403	-0.399	2.993
L	-1.403	-1.894	-4.516	5.094
O	2.434	0.711	1.673	3.038
Q	-1.501	1.273	0.148	1.974
R	0.473	1.949	-2.013	2.842
T	1.851	-0.965	-0.129	2.092
U	1.455	-0.567	-1.116	1.920
X	-5.271	-2.147	1.570	5.904
AVERAGE MEAN SQUARE ERROR	**2.654**	**1.918**	**2.141**	**3.912**

Table 63: **Control Structure Coordinates for Subjects 2 & 7**

CONTROL STRUCTURE COORDINATES (mm) SUBJECTS # 2 & 7			
POINT	X	Y	Z
C	258.035	260.026	172.004
E	-1.538	1023.008	-0.680
F	255.916	763.597	171.598
H	1024.296	1021.391	2.398
I	763.237	764.132	169.436
L	764.174	254.080	167.663
O	768.388	257.134	512.140
Q	1019.642	1022.701	681.292
R	765.568	767.091	509.065
T	0.399	1020.655	682.427
U	259.658	766.047	506.942
X	252.221	253.362	512.264

Table 64: **Reprediction Errors for Subjects 2 & 7**

REPREDICTION ERRORS (mm) SUBJECTS 2 & 7				
POINT	X	Y	Z	RESULTANT
C	2.035	4.026	1.444	4.737
E	-1.538	1.408	-0.680	2.193
F	-0.084	-2.103	0.998	2.329
H	2.696	-0.209	2.398	3.614
I	-2.463	-1.568	-1.164	3.143
L	-1.526	-1.920	-2.937	3.827
O	2.688	1.134	1.640	3.347
Q	-1.958	1.101	0.192	2.254
R	-0.132	1.391	-1.435	2.003
T	0.399	-0.945	1.327	1.678
U	3.658	0.347	-3.558	5.114
X	-3.779	-2.638	1.764	4.935
AVERAGE MEAN SQUARE ERROR	**2.356**	**1.936**	**1.944**	**3.617**

Table 65: **Control Structure Coordinates for Subject 3**

CONTROL STRUCTURE COORDINATES (mm) SUBJECT # 3			
POINT	X	Y	Z
C	260.577	259.893	171.322
E	-2.961	1022.384	-0.468
F	255.238	764.232	169.950
H	1024.869	1020.110	2.177
I	764.377	765.779	170.720
L	763.912	254.623	168.495
O	766.406	255.644	511.185
Q	1020.106	1022.819	680.306
R	765.399	767.963	510.195
T	2.195	1020.613	682.907
U	257.346	765.640	507.169
X	252.591	253.504	512.594

Table 66: **Reprediction Errors for Subject 3**

REPREDICTION ERRORS (mm) SUBJECT # 3				
POINT	X	Y	Z	RESULTANT
C	4.577	3.893	0.722	6.052
E	-2.961	0.784	-0.468	3.098
F	-0.762	-1.468	-0.650	1.777
H	3.269	-1.490	2.177	4.200
I	-1.323	0.079	0.120	1.330
L	-1.788	-1.377	-2.105	3.086
O	0.706	-0.356	0.685	1.046
Q	-1.494	1.219	-0.794	2.085
R	-0.301	2.263	-0.305	2.303
T	2.195	-0.987	1.807	3.010
U	1.346	-0.060	-3.331	3.594
X	-3.409	-2.496	2.094	4.716
AVERAGE MEAN SQUARE ERROR	**2.468**	**1.809**	**1.659**	**3.481**

Table 67: **Control Structure Coordinates for Subjects 8 & 9**

CONTROL STRUCTURE COORDINATES SUBJECTS # 8 & 9			
POINT	X	Y	Z
C	260.773	259.199	173.444
E	-3.026	1021.622	-2.992
F	256.823	764.271	173.472
H	1023.968	1020.182	1.838
I	764.623	768.273	172.260
L	762.884	253.709	165.092
O	767.004	255.947	512.764
Q	1020.622	1021.716	680.460
R	765.381	767.935	509.351
T	1.224	1021.686	682.246
U	257.877	764.008	507.667
X	251.888	254.652	510.926

Table 68: **Reprediction Errors for Subjects 8 & 9**

REPREDICTION ERRORS (mm) SUBJECTS # 8 & 9				
POINT	X	Y	Z	RESULTANT
C	4.773	3.199	2.844	6.411
E	-3.026	0.022	-2.992	4.255
F	0.823	-1.429	2.872	3.312
H	2.368	-1.418	1.838	3.316
I	-1.077	2.573	1.660	3.246
L	-2.816	-2.291	-5.508	6.597
O	1.304	-0.053	2.264	2.613
Q	-0.978	0.116	-0.640	1.175
R	-0.319	2.235	-1.149	2.533
T	1.224	0.086	1.146	1.679
U	1.877	-1.693	-2.833	3.797
X	4.112	-1.348	0.426	4.348
AVERAGE MEAN SQUARE ERROR	**2.558**	**1.805**	**2.665**	**4.112**

Table 69: Control Structure Coordinates for Subjects 5 & 10

CONTROL STRUCTURE COORDINATES SUBJECTS # 5 & 10			
POINT	X	Y	Z
C	260.095	259.113	173.931
E	-2.822	1022.541	-1.734
F	257.277	764.841	170.318
H	1024.209	1020.100	3.425
I	763.962	766.083	169.779
L	763.802	253.876	165.826
O	766.407	256.113	512.864
Q	1021.781	1022.204	680.390
R	763.915	769.022	509.147
T	1.133	1020.472	682.082
U	257.318	764.552	509.728
X	252.964	254.295	510.772

Table 70: Reprediction Errors for Subjects 5 & 10

REPREDICTION ERRORS (mm) SUBJECTS # 5 & 10				
POINT	X	Y	Z	RESULTANT
C	4.095	3.113	3.331	6.128
E	-2.822	0.941	-1.734	3.443
F	1.277	-0.859	-0.282	1.565
H	2.609	-1.500	3.425	4.559
I	-1.738	0.383	-0.821	1.960
L	-1.898	-2.124	-4.774	5.559
O	0.707	0.113	2.364	2.470
Q	0.181	0.604	-0.710	0.949
R	-1.785	3.322	-1.353	4.006
T	1.133	-1.128	0.982	1.876
U	1.318	-1.148	-0.772	1.911
X	-3.036	-1.705	0.272	3.493
AVERAGE MEAN SQUARE ERROR	**2.251**	**1.787**	**2.315**	**3.690**

Table 71: **Control Structure Coordinates for Subject 11**

CONTROL STRUCTURE COORDINATES SUBJECT # 11			
POINT	X	Y	Z
C	260.758	259.676	173.226
E	-2.698	1022.301	-1.590
F	255.526	764.337	171.706
H	1024.834	1020.371	2.652
I	764.522	765.330	169.220
L	763.417	254.314	167.527
O	766.870	256.295	512.421
Q	1021.149	1021.970	680.589
R	763.937	768.833	509.871
T	2.227	1020.351	683.103
U	256.484	766.532	507.472
X	253.041	252.890	510.361

Table 72: **Reprediction Errors for Subject 11**

REPREDICTION ERRORS (mm) SUBJECT # 11				
POINT	X	Y	Z	RESULTANT
C	4.758	3.676	2.626	6.561
E	-2.698	0.701	-1.590	3.209
F	-0.474	-1.363	1.106	1.818
H	3.234	-1.229	2.652	4.359
I	-1.178	-0.370	-1.380	1.852
L	-2.283	-1.686	-3.073	4.183
O	1.169	0.295	1.921	2.269
Q	-0.451	0.370	-0.511	0.776
R	-1.763	3.133	-0.629	3.650
T	2.227	-1.249	2.003	3.245
U	0.484	0.832	-3.028	3.177
X	-2.959	-3.110	-0.139	4.295
AVERAGE MEAN SQUARE ERROR	**2.446**	**1.961**	**2.058**	**3.750**

Table 73: **Control Structure Coordinates for Subject 12**

CONTROL STRUCTURE COORDINATES SUBJECT # 12			
POINT	X	Y	Z
C	260.944	260.187	173.799
E	-2.410	1022.194	-2.449
F	255.652	763.693	170.361
H	1024.322	1020.600	1.787
I	764.240	765.666	173.005
L	762.561	254.051	166.088
O	767.997	255.611	510.576
Q	1019.658	1022.031	680.654
R	766.397	769.076	509.327
T	1.498	1020.531	681.398
U	258.105	765.873	510.299
X	251.079	253.701	511.709

Table 74: **Reprediction Errors for Subject 12**

REPREDICTION ERRORS (mm) SUBJECT # 12				
POINT	X	Y	Z	RESULTANT
C	4.944	4.187	3.199	7.225
E	-2.410	0.594	-2.449	3.486
F	-0.348	-2.007	-0.239	2.051
H	2.722	-1.000	1.787	3.407
I	-1.460	-0.034	2.405	2.813
L	-3.139	-1.949	-4.512	5.832
O	2.297	-0.389	0.076	2.331
Q	-1.942	0.431	-0.446	2.039
R	0.697	3.376	-1.173	3.641
T	1.498	-1.069	0.298	1.864
U	2.105	0.173	-0.201	2.121
X	-4.921	-2.299	1.209	5.565
AVERAGE MEAN SQUARE ERROR	**2.864**	**2.020**	**2.106**	**4.089**

Table 75: **Control Structure Coordinates for Subjects 13 & 14**

CONTROL STRUCTURE COORDINATES (mm) SUBJECTS # 13 & 14			
POINT	X	Y	Z
C	259.833	260.236	173.495
E	-3.804	1022.739	-1.222
F	257.578	763.437	171.945
H	1023.978	1020.401	2.162
I	765.694	765.236	171.010
L	762.705	254.286	165.175
O	767.826	255.595	513.999
Q	1020.426	1022.133	680.994
R	763.251	769.617	508.287
T	0.732	1020.525	681.833
U	260.247	765.362	508.480
X	251.539	253.653	510.444

Table 76: **Reprediction Errors for Subjects 13 & 14**

REPREDICTION ERRORS (mm) SUBJECTS # 13 & 14				
POINT	X	Y	Z	RESULTANT
C	3.833	4.236	2.895	6.405
E	-3.804	1.139	-1.222	4.155
F	1.578	-2.263	1.345	3.069
H	2.378	-1.198	2.162	3.430
I	-0.006	-0.464	0.410	0.619
L	-2.995	-1.714	-5.425	6.430
O	2.126	-0.405	3.499	4.155
Q	-1.174	0.533	-0.106	1.294
R	-2.449	3.917	-2.213	5.122
T	0.732	-1.075	0.733	1.493
U	4.247	-0.338	-2.020	4.715
X	4.461	-2.347	-0.056	5.042
AVERAGE MEAN SQUARE ERROR	**2.964**	**2.164**	**2.482**	**4.430**

Table 77: **Control Structure Coordinates for Subject 15 (FS)**

CONTROL STRUCTURE COORDINATES (mm) SUBJECT # 15 (FS CONDITION)			
POINT	X	Y	Z
C	258.174	260.271	173.127
E	-3.351	1021.941	-3.457
F	258.415	764.244	174.954
H	1024.386	1020.035	1.540
I	764.400	766.000	172.417
L	763.220	254.752	165.014
O	767.086	254.376	513.385
Q	1019.365	1022.423	679.935
R	765.913	769.503	509.721
T	0.811	1020.808	682.616
U	2583243	764.710	507.262
X	253.377	254.142	510.070

Table 78: **Reprediction Errors for Subject 15 (FS)**

REPREDICTION ERRORS (mm) SUBJECT #15 (FS CONDITION)				
POINT	X	Y	Z	RESULTANT
C	2.174	4.271	2.527	5.418
E	-3.351	0.341	-3.457	4.827
F	2.415	-1.456	4.354	5.187
H	2.786	-1.565	1.540	3.547
I	-1.300	0.300	1.817	2.255
L	-2.480	-1.248	-5.586	6.238
O	1.386	-1.624	2.885	3.588
Q	-2.235	0.823	-1.165	2.651
R	0.213	3.803	-0.779	3.888
T	0.811	-0.792	1.516	1.893
U	2.243	-0.990	-3.238	4.062
X	-2.623	-1.858	-0.430	3.243
AVERAGE MEAN SQUARE ERROR	**2.275**	**2.076**	**2.976**	**4.283**

Table 79: **Control Structure Coordinates for Subject 15 (MS & NS)**

CONTROL STRUCTURE COORDINATES (mm) *SUBJECT # 15 (MS & NS CONDITIONS)*			
POINT	X	Y	Z
C	259.409	259.976	174.933
E	-2.222	1021.335	-3.628
F	256.628	764.192	173.613
H	1024.555	1021.926	2.526
I	762.935	764.700	172.648
L	763.765	254.207	163.171
O	766.964	256.068	512.681
Q	1020.185	1020.817	680.304
R	766.225	769.561	510.003
T	0.874	1021.865	682.466
U	258.352	765.065	506.460
X	252.393	253.525	511.386

Table 80: **Reprediction Errors for Subject 15 (MS & NS)**

REPREDICTION ERRORS (mm) *SUBJECT # 15 (MS & NS CONDITIONS)*				
POINT	X	Y	Z	RESULTANT
C	3.409	3.976	4.333	6.798
E	-2.222	-0.265	-3.628	4.262
F	0.628	-1.508	3.013	3.427
H	2.955	0.326	2.526	3.901
I	2.765	-1.000	2.048	3.583
L	-1.935	-1.793	-7.429	7.884
O	1.264	0.068	2.181	2.522
Q	-1.415	-0.783	-0.796	1.803
R	0.525	3.861	-0.497	3.928
T	0.874	0.265	1.366	1.643
U	2.352	-0.635	-4.040	4.718
X	-3.607	-2.475	0.886	4.464
AVERAGE MEAN SQUARE ERROR	**2.340**	**2.014**	**3.456**	**4.634**