AN ABSTRACT OF THE THESIS OF

Nicole L. Shivitz for the degree of Master of Science in Human Performance presented on November 30, 2001. Title: Adaptation of Vertical Ground Reaction Force due to Changes in Breast Support in Running.

Abstract approved: Redacted for privacy

Gerald A. Smith

Introduction: Sports bras offer different levels of breast support and allow for a wide range of vertical breast motion. Excessive breast motion during exercise causes discomfort and may discourage participation in regular exercise. Inadequate breast support may lead to adaptations in a woman's running mechanics. Purpose: This study aimed to determine the relationship of breast support to breast motion, ground reaction force, vertical stiffness, and stride frequency. Methods: Seventeen subjects of breast sizes 34C-38D ran on an instrumented treadmill while wearing low-, medium-, and high-support sports bras. Force and motion data were collected from which mechanical characteristics for each support condition were calculated. Repeated measures analysis of variance (ANOVA) was used for group analysis, but individual subject analysis using single factor randomized ANOVA formed the core of the study, which focused on the unique, individual subject responses to the three levels of breast support. Results: In the group analysis, breast motion decreased while active peak vertical force increased with support; other kinetic and kinematic variables were unchanged for the group. Each subject had the least amount of vertical breast motion in the high support condition. Twelve of the 17 subjects had an increase in active peak VGRF with an increase in support while fewer (43%)

increased impact peak VGRF (not including four subjects with a midfoot strike pattern for whom no impact peak was evident). Vertical stiffness decreased for most subjects as breast support increased with 59% having the greatest stiffness values at the lowest level of support. Finally, while there were significant changes in stride frequency for many subjects, the magnitude of the changes were relatively small compared to force and stiffness changes. Conclusions: Women in this study had decreased breast motion as breast support increased. In addition, many subjects had mechanical adaptations to increased support, which included increased vertical ground reaction force but decreased vertical stiffness.

Adaptation of Vertical Ground Reaction Force
due to Changes in Breast Support in Running

by

Nicole L. Shivitz

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented November 30, 2001
Commencement June 2002

Master of Science thesis of Nicole L. Shivitz presented on November 30, 2001.

APPROVED:

Redacted for privacy

Major professor, representing Human Performance

Redacted for privacy

Chair of Department of Exercise and Sport Science

Redacted for privacy

Dean of Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Redacted for privacy

Nicole L. Shivitz, Author

ACKNOWLEDGEMENT

I would like to take the time to thank the many people who have made my research at Oregon State University successful. First, I would like to thank my subjects who volunteered to participate in this study. Running in an unsupportive bra for any amount of time can be painful, and that many women would do so speaks to the importance of the research. Thank you to LaJean Lawson for introducing me to this area of research and for your vast knowledge of fabric and design, physiology, and biomechanics. It was a joy working with you. Thank you for sharing your own experiences that taught me that life happens, even when pursuing an advanced degree.

I would like to thank my advisor, Gerald Smith. Your classes were always fun and interesting while being challenging. You were always available whether you were on sabbatical or I was working from Eugene. It is not easy completing a degree an hour away, but your patience and advice via email made it possible. Thank you to my committee members, Terry Wood and Michael Schuyler. Terry was always available to dispense statistics advice and explanation. I spent a majority of my time for two terms in Dr. Schuyler's electronics and computer interfacing labs, where not only did I learn something about electronics, but the confidence to experiment! Thank you to Dr. Jeff Woldstad for being my graduate representative and voicing helpful opinions at the proposal meeting.

My friends, past and present, made a big difference in my Oregon experience. Friends I made while at OSU whom I'd like to thank are Jen Wright, Marie Hornyk (my wine tasting buddy), Jane Lariviere (proof that you CAN do crew and "other things"), Jeremy Bauer, and Iain Hunter. You made OSU a fun place to be. Thank you to friends at the University of Oregon Motor Control Laboratory. Working for you has made my end product that much better. Thank you to Laura Adomaitis, who is a dear friend and a voice of reason when things are crazy. Finally, to Tami and the "couch"- Elana, Cindy, Jen, Katie, and Kelly. It is amazing how supportive friends can be, even when 3000 miles separate you.

I would like to thank my parents, Philip and Roberta Robert, and my husband's parents, William and Kathleen Shivitz. They have supported me with love and encouragement and I am very grateful for the wonderful relationship I have with both my parents and my in-laws.

Finally, I have to thank my husband, Robert Shivitz. From the beginning of my pursuing a Master's degree, he has offered support, love, and much needed encouragement. He talked me into quitting one of my jobs the first year of grad school when I was paying out-of-state tuition, insisting that my sanity was more valuable than the loan we would take out instead. Rob always has supported my decisions, even if those decisions delayed my finishing this thesis. All of the very small and very large things you have done for me are appreciated, and without you this process would have been infinitely more difficult.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

Adaptation of Vertical Ground Reaction Force
due to Changes in Breast Support in Running

Chapter 1

Introduction

1.1 Background

There has been a rapid increase in the interest and importance of physical fitness due to an increased awareness of the physiological and psychological health benefits. Physiological health benefits of regular aerobic exercise include the reduction of the possibility of coronary artery disease, diabetes, and cancer (Donatelle, Snow, and Wilcox, 1999). Psychological benefits of physical fitness include increased self-esteem, confidence, and decreased stress (Hassmen, P., Koivula, N. and Uutela, A., 2000; Carmack, C.L., Boudreaux, E., Amaral-Melendez, M., Brantley, P.J. and de Moor, C., 1999; Donatelle, Snow, and Wilcox, 1999; Fahey, T.D., Insel, P.M., and Roth, W.T., 1997). Regular aerobic exercise like running is a popular choice for fitness because it can be done anywhere, it is inexpensive, and running can fit into most time schedules.

In order for an individual to exercise consistently, he or she must remain motivated. Factors that may influence motivation are proper equipment, clothing, participation in an appropriate activity for one's lifestyle, and comfort. For women participating in exercise, breast support is crucial (Haycock, 1978). A sports bra that provides adequate support by restricting breast motion and increasing comfort may increase motivation to remain in a fitness program.

Without adequate breast support, women often find exercise to be uncomfortable and may alter their running pattern in attempt to reduce breast motion. Such adaptations are likely to affect kinetic characteristics and decrease exercise enthusiasm and performance. Runners wearing sports bras that offer various amounts of breast support will experience different levels of comfort (Lorentzen and Lawson, 1987) that may result in different running characteristics.

In order to further study the effectiveness of sports bras, it was important to explore a relationship between breast support (defined by amount of breast motion) and its affect on running kinematics and kinetics. There are no published studies that compare running characteristics for different amounts of breast motion. The current study analyzed breast support's effect on vertical breast motion (VBM), vertical stiffness, the active peak vertical ground reaction force (APGRF), impact peak ground reaction force (IPGRF), and stride frequency. Vertical breast motion is the vertical displacement of the breast relative to the body. It has been established that different sports bra styles result in different amounts of vertical breast motion (Eden et al., 1992; Haycock, 1986; and Lawson and Lorentzen, 1990).

Changes that affect kinetic characteristics when running might be expected to result in an adaptation of one or more other characteristics. If a runner experiences discomfort due to lack of breast support and tries to modify her running style, a change may occur in kinematic or kinetic characteristics. Motivation to exercise may decrease if the breast motion is large enough to cause women to have different running characteristics because they are most likely doing so to reduce pain or discomfort. Sports bras designed to greatly reduce vertical breast motion may allow a woman to participate freely in exercise without making compensations or restricting her activities.

1.2 Operational Definitions

Vertical Breast Motion (VBM): Describes the vertical displacement of the breast relative to the trunk, which acts as a reference to the body. Markers are placed on the breast and on the trunk. The position data of the breast are subtracted from the trunk, and the resulting value describes vertical breast motion.

Bra-Breast Stiffness (BBS): Used to describe the interaction between the breast and the bra, BBS is the acceleration of the breast divided by vertical breast displacement relative to the trunk.

Ground Reaction Force (GRF): The force exerted on the ground by the foot during standing, walking, and running. It can be measured in the vertical, medial-lateral, and anterior-posterior directions. *Vertical ground reaction forces (VGRF)* were measured in this study.

Active Peak Ground Reaction Force (APGRF): In the force curve for an individual step, it is the maximum ground reaction force exerted.

Impact Peak Ground Reaction Force (IPGRF): In the force curve for an individual step, it is the maximum initial ground reaction force that is mainly due to heel strike. An IPGRF is not always present, especially in the case when initial step contact is with the midfoot.

Stance Time: The amount of time the foot remains in contact with the ground during walking or running.

Stride Frequency (SF): How often during one second one stride is completed (the inverse of stance time).

Vertical Stiffness (VS): Describes the relationship of the vertical motion of the body's center of mass (COM) during stance and vertical ground reaction force.

Center of Mass (COM): Describes the position of an object's center. In this study, the vertical displacement of the COM is needed to calculate vertical stiffness, and is derived by performing a double integration on acceleration calculated from ground reaction forces.

Chapter 2

Adaptation of Vertical Ground Reaction Force due to Changes in Breast Support in Running

Nicole L. Shivitz and Gerald A. Smith

Department of Exercise and Sport Science
Oregon State University, Corvallis, Oregon

2.1 Introduction

For women participating in exercise, breast support is crucial (Haycock, 1978). A sports bra that provides adequate support by restricting breast motion and increasing comfort may increase motivation to remain in a fitness program. The need for wearing sports bras has been well established and many authors have found breast pain linked to excessive breast motion while running (Eden, Valiant, Lawson, and Himmelsbach, 1992; Haycock, 1986; and Lawson and Lorentzen, 1990). It has also been established that different sports bra styles result in different amounts of vertical breast motion (Eden et al., 1992; Haycock, 1986; and Lawson and Lorentzen, 1990). Research showed that excessive motion caused more breast pain for C and D sizes over A and B sizes, resulting in the idea that sports bras need to be specially designed to address the needs of larger sizes (Lorentzen and Lawson, 1987).

In order to further study the effectiveness of sports bras, it was important to explore a relationship between breast support (defined by amount of breast motion) and its affect on running kinematics and kinetics. There are no published studies that compare running characteristics for different amounts of breast motion. Research does tell us that factors affecting gait during running and vertical ground reaction forces (GRFs) include running speed, stance time, and stride frequency. Ground reaction forces represent the force the ground exerts on the foot which is transmitted through the body. It has been reported that an increase in running speed is associated with increases in active and impact peak vertical GRFs and average vertical GRF (Miller, 1990; Munro, Miller, and Fuglevand, 1987; Cavanagh and LaFortune, 1980). In the current study where speed was kept constant, other factors such as breast pain or discomfort due to insufficient breast support may have contributed to any changes in VGRF.

Leg stiffness refers to the stiffness of the leg in contact with the ground and vertical stiffness describes the vertical motions of the body's center of mass (COM) during stance time (Heise and Martin, 1998). Leg stiffness and vertical stiffness in both hopping and running have been shown to change due to surface stiffness, stride frequencies, foot strike position, and foot orientations. An increase in surface stiffness has been repeatedly proven to cause a decrease in leg stiffness in both hopping and running (Farley, Houdijk, van Strien, and Louie, 1998; Ferris, Louie, and Farley, 1998; Ferris and Farley, 1997). However, when surface stiffness is kept constant, a change in stride frequency or stance time affects leg and vertical stiffness of the runner. Changing stride frequencies alters the angle swept by the leg, which results in a change in leg stiffness. Farley and Gonzalez (1996) varied stride frequency from 26% below each subject's natural stride frequency to 36% above each subject's natural stride frequency. Results showed an increase in leg stiffness with increased stride frequency, and there was also a decrease in vertical GRF, decrease in stance time, and a decrease in the magnitude of vertical displacement of the COM that resulted in an increase in vertical stiffness. If a runner experiences discomfort due to lack of breast support and alters one of these running characteristics, a change may occur in any of the other gait characteristics mentioned above.

Without adequate breast support, women often find exercise to be uncomfortable and may alter their running pattern in attempt to reduce breast motion. Such adaptations are likely to affect kinetic characteristics and decrease exercise enthusiasm and performance. Runners wearing sports bras that offer various amounts of breast support will experience different levels of comfort that may result in different running characteristics. Currently, no studies have reported statistically or practically significant changes in running characteristics with various levels of breast support. Boschma (1995) studied kinematic changes with breast sizes B, C, and D for moderate and full breast support for 15 subjects. There were no statistically significant differences between support levels for stride length, stride rate, vertical trunk displacement, and arm range of motion even though there were significant differences in vertical breast displacement due to the level of support (Boschma, 1995). In the current study, we used a design with multiple single-subject analyses making it possible to detect significant changes in kinetic variables due to increasing breast support on a case by case basis in order to detect population trends.

The purpose of the current study was to determine if characteristics of running change with levels of breast support. Specifically, the study addressed the question: Does active peak vertical force, impact peak force, stride frequency, vertical stiffness, or vertical breast motion during running differ with low, medium, and high levels of breast support? We predicted an increase in breast support was expected to be associated with a decrease in vertical stiffness, stride frequency, and vertical breast motion (VBM) while there should be an increase in vertical ground reaction forces. Vertical stiffness is derived from dividing the maximum VGRF by the displacement of the COM of the body. A decrease in the displacement of COM will cause an increase in vertical stiffness. One would expect the subject, running with a less supportive bra, to try to decrease her vertical body movement (COM) when compared to a more supportive bra. With an increase in breast support, we expected an increase in APGRF and more COM displacement (also represented by trunk motion measured by sternum movement) to give a net result of lower vertical stiffness.

2.2 Methods

Seventeen women volunteers over the age of 18 participated in this study. Subjects were moderately active (defined by participating in exercise such as aerobics, soccer, running, etc. at least once per week) and were required to be able to sustain a pace of 2.68 m/s running on a motorized treadmill for several minutes. They also wore a bra size of 34-42 inches, cup sizes C or D. The Oregon State University Institutional Review Board for Protection of Human Subjects approved this research protocol and each subject has signed an approved consent form (Appendix C).

Subjects of this study ran wearing a sports bra with low, medium, or high support characteristics as determined by material, structure, and style differences. They ran on a motorized treadmill with instrumentation allowing the measurement of vertical GRF data. Concurrently, a motion analysis system recorded three-dimensional coordinates used to determine the position of the right breast relative to the trunk. This procedure was repeated with each of the bra support levels for each subject.

Before data collection, each subject was weighed and her right leg measured from greater trochanter to floor. The subject was instructed on treadmill running and required to warm up and to adapt to the treadmill with 5-10 min of walking and slow running. Subjects then ran on the instrumented treadmill at a 2.68 m/s pace at 0% grade for 40s for each of three sports bra support conditions (assigned to be worn in counterbalanced order, which randomly assigns each subject with one of the six possible combinations). The subject had reflective markers placed on the sternum and over the right nipple on the outside of the sports bra. The nipple has been shown to be an accurate indicator of breast motion in comparison to other breast locations (Mason, Page, and Fallon, 1999). From this collection, it was possible to characterize the frontal plane motion of the breast for the low-, medium- and high-support sports bra conditions. Vertical displacement of the breast with respect to the trunk was determined from the motion records. Simultaneously, vertical GRFs were collected from the treadmill. Force characteristics such as active peak vertical force, impact peak vertical force, vertical stiffness, and stride frequency were determined from the force data for each stride during the 40 s recording period.

The motion data were collected using the MacReflex system Version 3.0 (MacReflex, 1995). The set-up consisted of three MacReflex infrared cameras used to record position data in 3-D. These cameras recorded the X, Y, and Z positions of reflective markers without visual images. First, the MacReflex standard 9-point calibration structure was used for 3-D calibration. The MacReflex software is run on a Macintosh computer and is the interface from which the user controls the cameras for calibration and data collection. The cameras were recalibrated each day prior to data collection. The camera positions illustrated in Figure 2-1 optimized marker visibility and eliminated the chance of recording extraneous reflections. The position data were collected at a sampling frequency of 120 Hz. Vertical breast motion was determined by

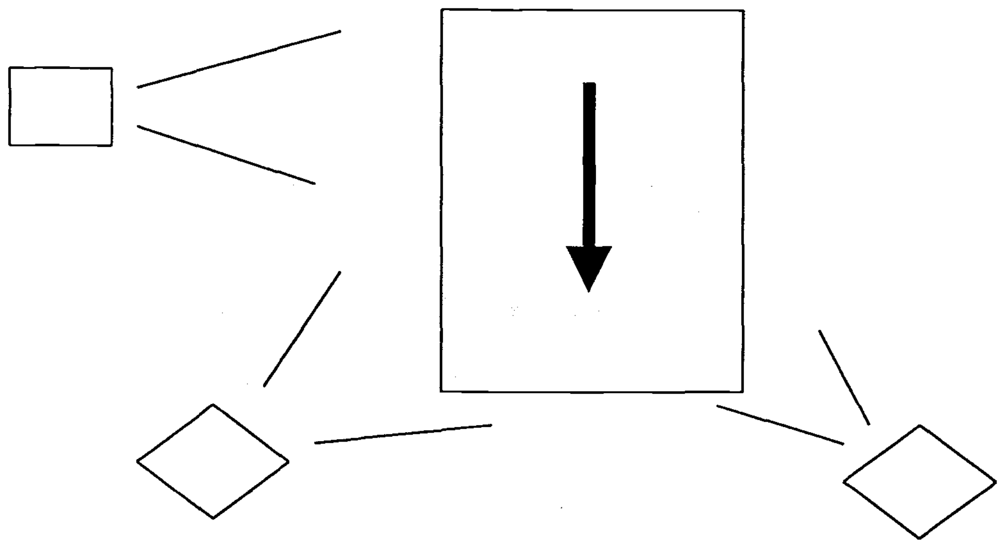

Figure 2-1. MacReflex camera configuration with treadmill for data collection.

using the sternum as a reference point from which to separate whole body motion from breast motion.

In addition, a variable called Bra-Breast Stiffness (BBS) was calculated. Bra-Breast Stiffness was used to describe the interaction between the breast and the bra as a system and was calculated by dividing the peak vertical acceleration of the breast in the bra with respect to the trunk and dividing it by the vertical displacement of the breast. Vertical acceleration of the breast was calculated from the position data; then the maximum acceleration point was used in the calculation of BBS. The units are in g's (gravity) per cm.

Vertical GRF data were collected at a sampling frequency of 500 Hz using a Quinton Model Q55 treadmill (Figure 2-2) previously instrumented with 6 piezoelectric force transducers (PCB Piezotronics 208A03 and 208A02) embedded under the treadmill bed (Fewster, 1996). Each transducer signal was amplified and sent to a DAS16 board into a PC. As suggested by Fewster (Fewster, 1996), the force treadmill has been permanently fixed to the floor, and the transducers were energized two hours prior to data collection. The treadmill was also re-zeroed prior to each trial to decrease the drift of the force transducers. Appendix A describes in detail the validity and reliability testing of this instrumented treadmill.

The software used for force collection was a Visual BASIC computer program (Darren Dutto, Biomechanics Lab, Oregon State University, 1999) that collected the force transducer outputs and saved them to a file.

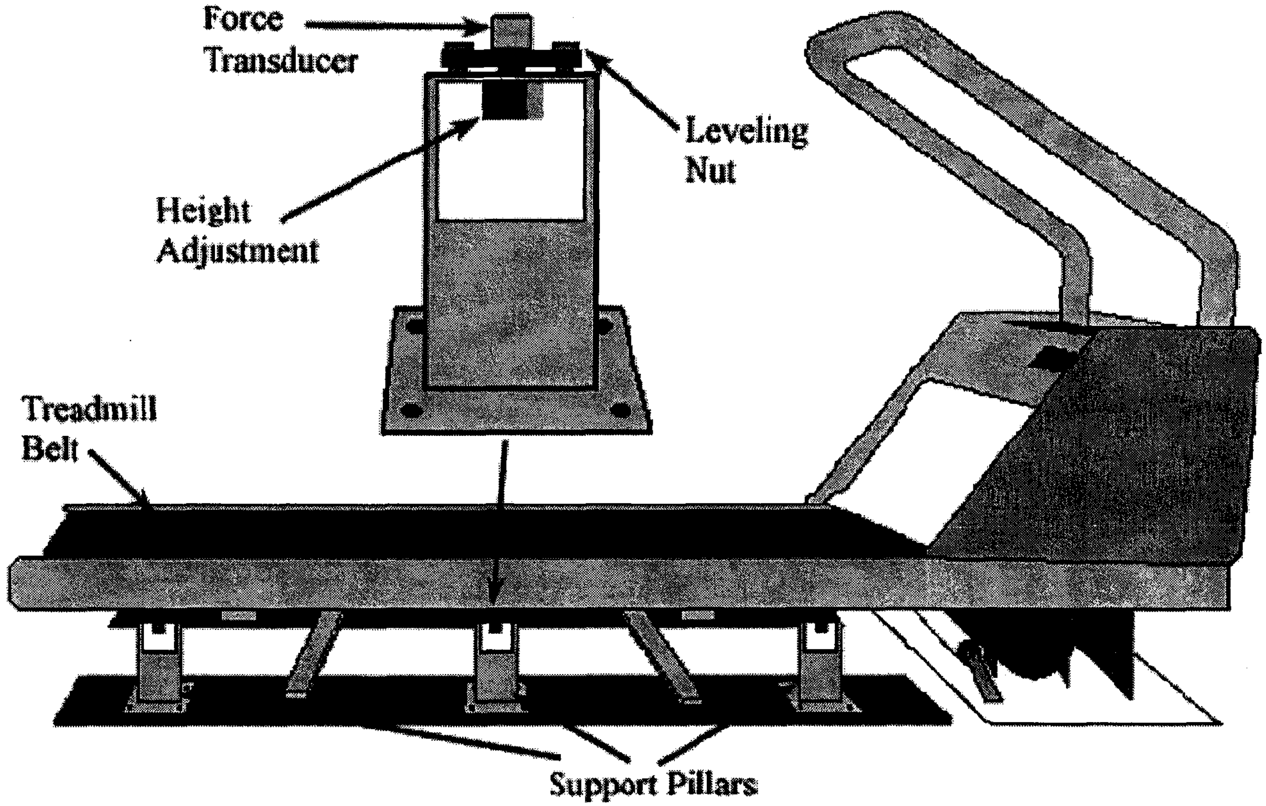

Figure 2-2. OSU Instrumented treadmill. Shown is an approximation of the location of the force transducers on the support pillars under the treadmill (used with permission, Hunter, 2001).

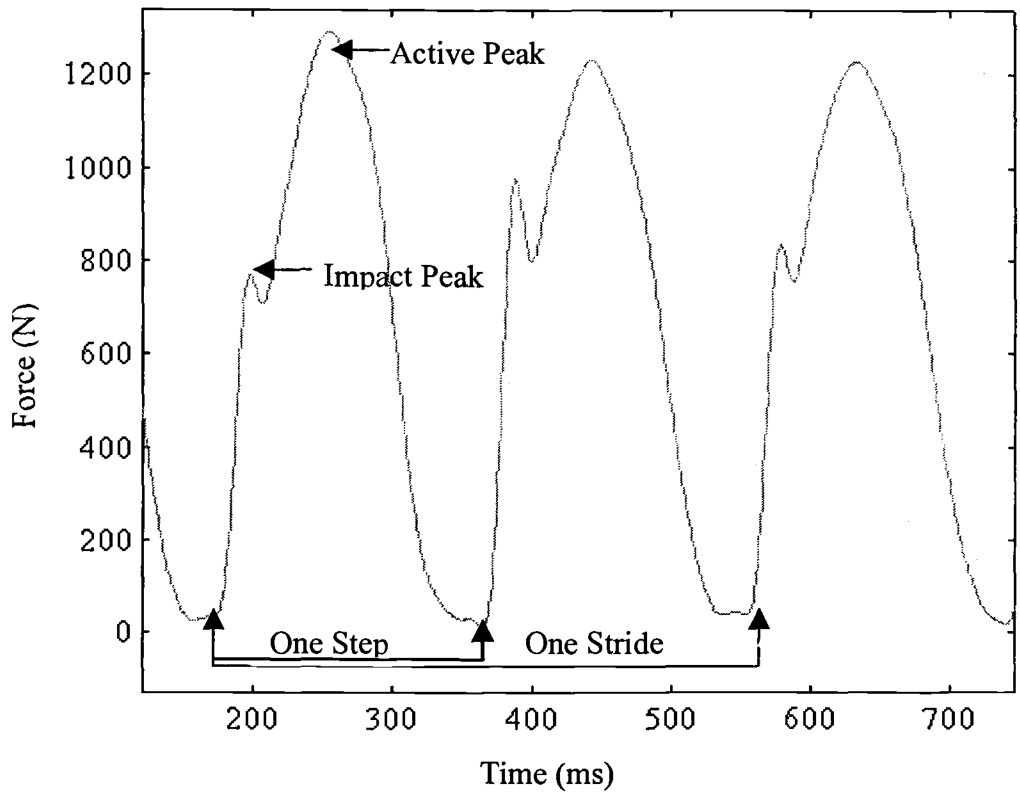

Figure 2-3. An example of force curves for a series of three running steps.

The force signals (Figure 2-3) were used to determine the active peak vertical GRF (the maximum vertical GRF) and impact peak vertical GRF (maximum force upon foot impact). Stride frequency is the inverse of the amount of time it takes between one heel strike and the next heel strike on the same foot (one stride length). A minimum vertical force of 30 N served as the criterion to indicate ground contact and toe off (Munro, Miller, and Fuglevand, 1987).

The spring-mass model shown in Figure 2-4 was used to determine the effective vertical stiffness using vertical motion of the center of mass of the subject during ground contact phase. The spring-mass model assumes the leg in contact with the ground acts as

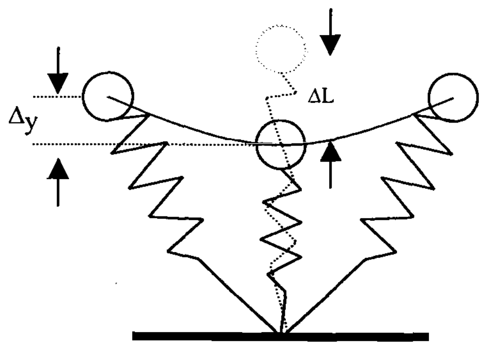

Figure 2-4. Running depicted as a simple spring-mass model. (adapted from McMahon and Cheng, 1990; Farley and Gonzalez, 1996).

a spring and the subject's mass is a point mass on top of the spring. This model has been used extensively in the literature to compute both leg stiffness and vertical stiffness (McMahon and Cheng, 1990; Farley, Houdijk, van Strien, and Louie, 1998; Ferris, Louie, and Farley, 1998; Ferris and Farley, 1997; Heise and Martin, 1998). The equation used for vertical stiffness is:

$$\text{kvert} = F\max / \Delta y$$

where F_{max} is the active peak VGRF and Δy is the vertical displacement of the body's center of mass (McMahon and Cheng, 1990). The vertical displacement of the body's center of mass was calculated from the GRFs by double integration of the vertical acceleration equation:

$$a_z(t) = (F_z(t) - BW) / m$$

$F_z(t)$ is the VGRF during stance, BW equals body weight, and m equals body mass. Stiffness values were normalized to body weight and leg length.

A Matlab (The Mathworks, v. 6) computer program (Appendix E) was used to calculate the above measures. The force data were first filtered using a low-pass 4th order Butterworth filter (cutoff 60Hz). Data were analyzed from both inter-subject and intra-subject perspectives.

Previous research studying the effects of breast motion on running kinematics has failed to yield significant statistical results in part due to large inter-subject variability. To address this issue, data in the study were first analyzed for each subject separately. Data screening for statistical assumptions, outliers, and missing data preceded statistical analysis. The *SPSS for Windows* version 10.0 (SPSS, 1999) computer statistical analysis package was used to run the statistical analysis on 90 steps for each subject under each support condition.

Single-subject analysis was performed in order to detect intra-subject differences in the dependent measures among the three levels of support. For each subject, a 1-way randomized ANOVA design using a General Linear Model was used to compare characteristics across three levels of support. Because of multicollinearity among the dependant variables, a separate analysis was performed for each of the dependent variables. To control inflation of the Type I error rate due to running multiple ANOVAs, alpha was adjusted so that for each subject the error rate was less than .05 with an α-level of .01. Tukey's post-hoc tests were computed in order to determine statistically significant effects.

Variability between subjects was expected to be considerably larger than intra-subject variability. Therefore, despite individual subjects with significantly different characteristics across support, group differences were less likely to be detected. A repeated measures ANOVA was performed to make the group characteristic comparisons. Seventeen subjects were required to detect a difference of mean values with a medium effect size with statistical power of at least .80 at α=.01 (Barcikowski and Robey, 1985). The literature has demonstrated a high variability between subjects which may make it difficult to statistically detect characteristic differences due to varying levels of breast support. The group analysis was carried out in order to provide a thorough analysis even though we expected to find significant results only in the single subject analysis.

2.3 Results

A single subject design was used in this study which allowed individual assessment of response. For each subject, single factor ANOVAs were run with follow-ups using Tukey post-hoc tests. The results of the analysis of each subject for each variable are presented separately in order to allow the reader to see trends easily where trends exist. Inter-subject RMANOVA results are included at the bottom of each chart.

2.3.1 Vertical Breast Motion

Figure 2.5 illustrates the typical displacement graph that represents VBM. Vertical Breast Motion averages and standard deviations are reported in Table 2-1. The

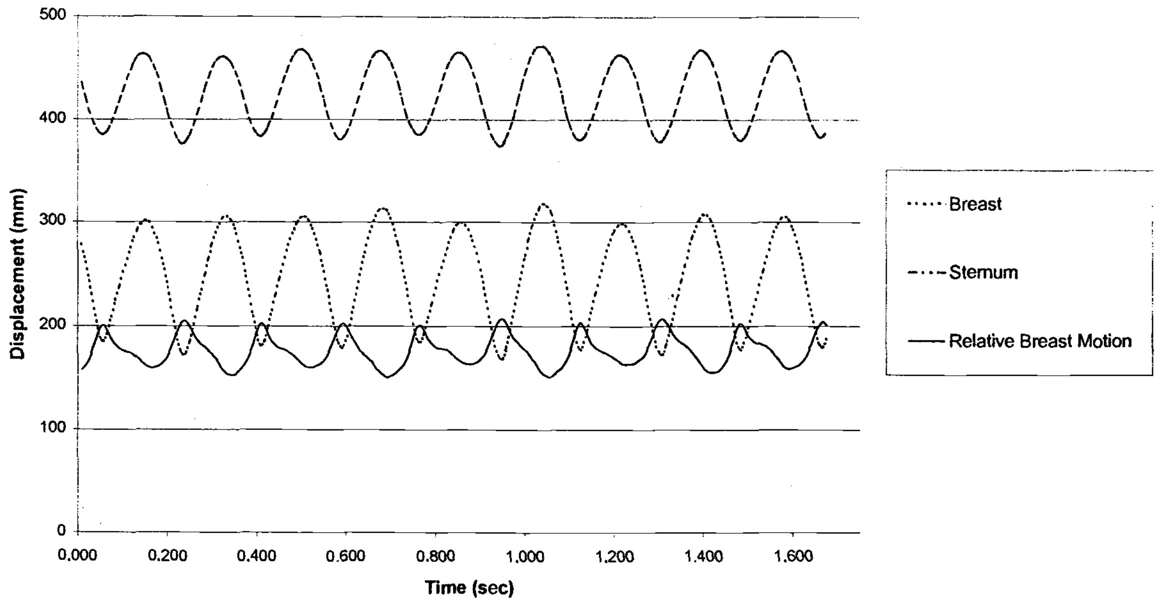

Figure 2-5. An example of motion of the sternum, breast, and resultant motion.

group means for the inter-subject analysis are at the bottom of the chart. Notice that the SDs for the intra-subject analyses range from 2 – 7 mm and the SDs for the inter-subject analysis were three times as high. Vertical Breast Motion showed statistically significant changes in the inter-subject analysis and it also decreased significantly between the low and high support condition for all intra-subject analyses. For 10 out of 17 subjects, as the level of support increased from low to high, the VBM decreased accordingly. One subject (s16) had no significant difference between the medium and high conditions, but both showed significantly smaller VBM than the low condition. Two subjects (s08, s12) had no significant difference between the low and medium conditions, but both showed significantly larger VBM than the high condition. Finally, four subjects (s02, s09, s13, and s14) had greater VBM in the medium support than the low support but still had significantly lower VBM in the high condition.

There are a few possible explanations for the last case mentioned. During data collection, it was observed that in the low support condition the breast was very loose inside the bra due to the lack of support. The breast appeared to move around inside the bra, and it is possible that excess movement occurred that was not recorded because the nipple marker was on the outside of the bra unable to record movement of the breast within the bra due to such excess movement. Three out of the four instances were size D cup, while only 1 out of the 13 subjects that yielded expected results was a D, comparatively. Thus, the low condition bra may have had even worse support for larger breasts, but this may not have been entirely demonstrated in the data.

Another possibility is that the low support bra actually provided more support than the medium support bra. In order to try to determine this, the bra-breast stiffness was calculated. This was an attempt to try and evaluate the interaction between the bra and breast while running by measuring the acceleration of the breast and dividing by breast displacement relative to the trunk. This calculation was described in the methods section and will be further described in the following section.

Note that in a curve of trunk displacement minus breast displacement, the positive relative peak is the breast moving downwards relative to the sternum (Figure 2-5). Figure 2-6 is a curve of the velocity of the VBM, where the peaks in velocity occur when the breast is moving down relative to the sternum. Finally, Figure 2-7 displays acceleration of the breast. The absolute maximum acceleration point was used in the calculation of BBS.

Table 2-1. Means and SD of Vertical Breast Motion (mm).

Subject # and Size	Support Level Low	Medium	High	P-value	Significance of Tukey Low-Med	Low-High	Med-High
s01-36C	23.5 (2.1)	19.6 (2.1)	17.0 (2.0)	< 0.01	< 0.01	< 0.01	< 0.01
s02-36D	69.7 (7.5)	76.8 (5.5)	51.5 (4.4)	< 0.01	< 0.01	< 0.01	< 0.01
s03-36C	76.9 (.5)	69.2 (.5)	45.5 (.5)	< 0.01	< 0.01	< 0.01	< 0.01
s04-36C	48.6 (2.9)	37.4 (3.6)	21.3 (3.7)	< 0.01	< 0.01	< 0.01	< 0.01
s05-36C	33.2 (6.0)	27.7 (5.5)	22.1 (6.5)	< 0.01	< 0.01	< 0.01	< 0.01
s06-34D	48.4 (5.2)	44.4 (5.5)	28.9 (4.9)	< 0.01	< 0.01	< 0.01	< 0.01
s07-36C	50.3 (6.4)	44.6 (5.7)	29.3 (4.9)	< 0.01	< 0.01	< 0.01	< 0.01
s08-38D	67.9 (7.7)	69.5 (6.7)	41.0 (6.9)	< 0.01	0.281	< 0.01	< 0.01
s09-38D	58.5 (4.6)	67.6 (4.6)	44.9 (5.9)	< 0.01	< 0.01	< 0.01	< 0.01
s10-34C	34.6 (4.9)	32.5 (3.8)	24.9 (5.3)	< 0.01	< 0.01	< 0.01	< 0.01
s11-34C	no data	38.4 (2.8)	27.9 (3.9)	< 0.01			< 0.01
s12-36C	35.4 (5.6)	35.6 (4.1)	19.0 (3.4)	< 0.01	0.945	< 0.01	< 0.01
s13-34D	26.2 (2.2)	28.5 (3.6)	21.2 (5.1)	< 0.01	< 0.01	< 0.01	< 0.01
s14-38C	51.4 (5.3)	58.6 (8.1)	52.1 (8.5)	< 0.01	< 0.01	< 0.01	< 0.01
s15-34C	37.5 (5.8)	30.4 (4.4)	19.4 (6.2)	< 0.01	< 0.01	< 0.01	< 0.01
s16-34C	40.1 (4.7)	35.9 (5.7)	35.9 (5.5)	< 0.01	< 0.01	< 0.01	0.998
s17-34C	48.1 (6.4)	44.5 (6.4)	35.1 (4.7)	< 0.01	< 0.01	< 0.01	< 0.01
Group Mean(SD)	46.9(15.5)	45.2(17.7)	31.9(12.1)	< 0.01			

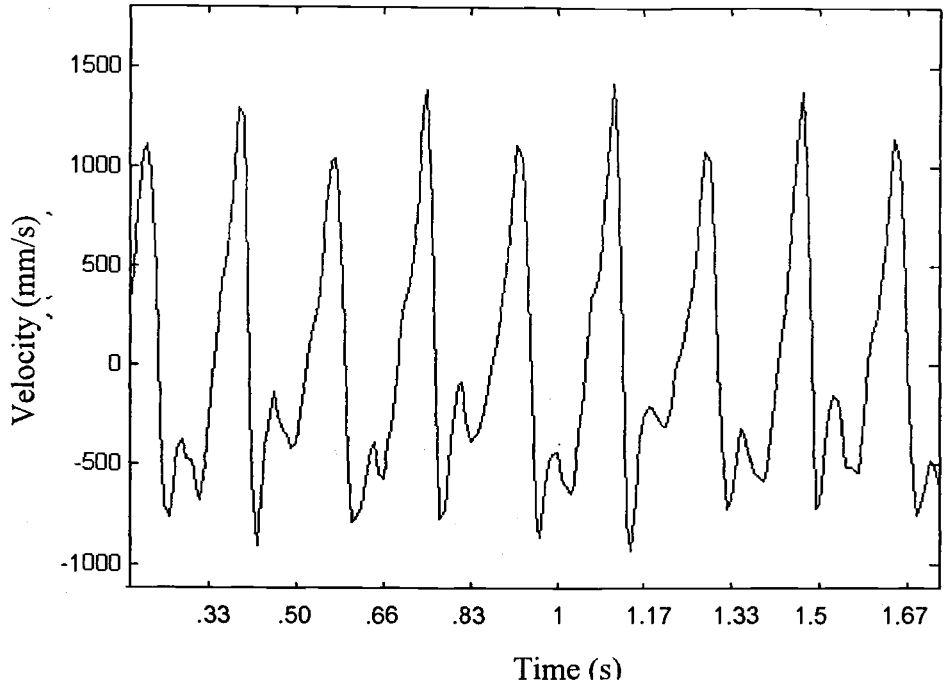

Figure 2-6. Breast motion velocity.

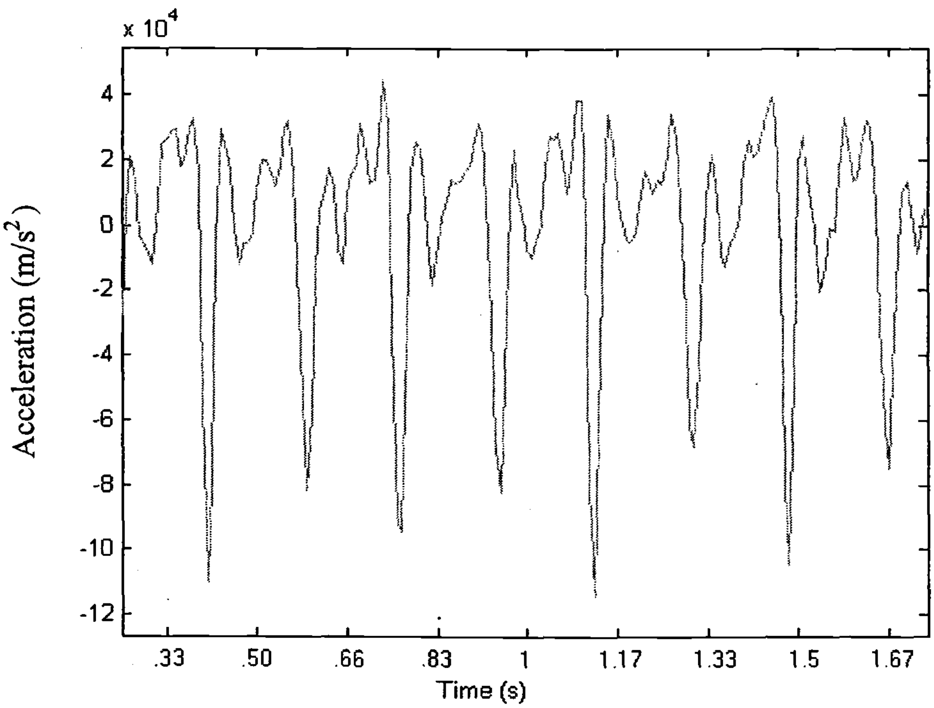

Figure 2-7. Breast motion acceleration.

Typically, "stiffness" measurements increase resulting in a decrease in motion (for example vertical and leg stiffness). In our measurements of BBS, a larger value indicated more movement. In most cases, as the VBM decreased with greater support, the BBS value decreased (Table 2-2). This variable was calculated in order to help give more information regarding breast movement and perhaps explain the four subjects where the medium condition appeared to give less support than the low condition based on the VBM numbers. In subject s02, the BBS values were consistent with the VBM measurements. One subject (s09) showed the medium and low conditions having about the same BBS value, s14 showed a decreasing stiffness as shown in most cases, and s13 showed an increase in stiffness from low to high. Note that these calculations were performed only for descriptive purposes and that statistics were not performed.

Table 2-2. Bra-Breast Stiffness (BBS) values (g's/cm)

Subject # and Size	Support Level Low	Medium	High
s01-36C	1.98	1.85	1.63
s02-36D	2.24	2.64	2.01
s03-36C	1.99	1.95	1.35
s04-36C	1.67	1.68	1.39
s05-36C	1.79	1.69	1.32
s06-34D	2.36	2.09	1.86
s07-36C	1.83	1.72	1.28
s08-38D	1.83	1.67	1.71
s09-38D	1.94	1.95	1.64
s10-34C	2.12	2.32	1.72
s11-34C	no data	2.72	1.89
s12-36C	2.15	2.28	1.96
s13-34D	1.67	1.81	1.91
s14-38C	1.75	1.65	1.44
s15-34C	1.82	1.66	1.56
s16-34C	2.45	2.04	2.41
s17-34C	1.99	2.48	2.23
s01-36C	1.98	1.85	1.63

2.3.2 Active Peak Vertical Ground Reaction Forces

The APGRF is typically the greatest amount of force exerted during a running step. It was predicted that this force would increase when the level of breast support increased. Twelve out of 17 subjects did show an increase in APGRF with an increase in breast support. Two subjects showed a decrease (s10, s15), two subjects had inconsistent changes (s07, s16), and one subject showed no significant difference (s08). The means and standard deviations are listed in Table 2.3. The inter-subject analysis result is at the bottom of the chart. The p-value was .011. Again, the variability of the group analysis is about 2-3 times that of the intra-subject analyses.

2.3.3 Impact Peak Vertical Ground Reaction Forces

The IPGRF is the peak in force at initial heel contact in a running step. We Predicted that the IPGRF would increase when the level of breast support increased. Subjects 10, 12, and 16 did not have impact peaks, possibly due to subjects being mid-foot strikers; therefore results from the remaining 14 subjects were analyzed (Table 2-4). Seven subjects (s01, s02, s03, s06, s07, s13, s17) had an increase in the magnitude of the IPGRF when breast support increased. One subject (s09) showed a decrease in IPGRF, four subjects had no significant difference (s05, s08, s14, s15), and two subjects had an unclear pattern with increase in support (s04, s11). Subject 14 (although statistically showed no significant difference), whose IPGRF increased from low to high, had no impact peak for the medium support condition. In the inter-subject analysis, the impact peak showed no statistical significant difference ($p = .644$). The variability was twice as high as the single subject variability.

Table 2-3. Active Peak Vertical Ground Reaction Force means and standard deviations (BW) for each subject.

Subject # and Size	Support Level				Significance of Tukey		
	Low	Medium	High	P-value	Low-Med	Low-High	Med-High
s01-36C	no data	1.91(.07)	1.96(.06)	< 0.01			
s02-36D	1.84(.04)	1.96(.05)	1.98(.05)	< 0.01	< 0.01	< 0.01	0.025
s03-36C	1.75(.04)	1.77(.04)	1.83(.04)	< 0.01	< 0.01	< 0.01	< 0.01
s04-36C	1.96(.04)	2.01(.04)	2.02(.03)	< 0.01	< 0.01	< 0.01	0.064
s05-36C	1.93(.04)	1.98(.04)	1.97(.04)	< 0.01	< 0.01	< 0.01	0.361
s06-34D	1.90(.04)	1.92(.05)	1.99(.04)	< 0.01	< 0.01	< 0.01	< 0.01
s07-36C	2.09(.07)	2.21(.08)	2.10(.07)	< 0.01	< 0.01	0.570	< 0.01
s08-38D	2.01(.07)	2.02(.07)	2.01(.05)	0.379	0.381	0.952	0.553
s09-38D	1.93(.08)	1.98(.08)	1.95(.09)	< 0.01	< 0.01	0.397	0.017
s10-34C	2.46(.04)	2.40(.04)	2.40(.04)	< 0.01	< 0.01	< 0.01	0.932
s11-34C	2.07(.05)	2.20(.05)	2.18(.05)	< 0.01	< 0.01	< 0.01	0.031
s12-36C	1.94(.05)	2.09(.05)	2.07(.04)	< 0.01	< 0.01	< 0.01	< 0.01
s13-34D	1.73(.03)	1.72(.05)	1.81(.06)	< 0.01	0.069	< 0.01	< 0.01
s14-38C	2.09(.06)	2.15(.06)	2.11(.05)	< 0.01	< 0.01	0.010	< 0.01
s15-34C	1.80(.05)	1.77(.05)	1.79(.05)	< 0.01	< 0.01	0.273	0.128
s16-34C	2.53(.15)	2.45(.10)	2.55(.11)	< 0.01	< 0.01	0.700	< 0.01
s17-34C	2.48(.10)	2.53(.08)	2.55(.09)	< 0.01	< 0.01	< 0.01	0.314
Group Mean(SD)	2.03(0.24)	2.07(0.24)	2.08(0.24)	0.011			

Table 2-4. Impact Peak Vertical Ground Reaction Force means and standard deviations (BW) for each subject.

Subject # and Size	Support Level			Significance	Significance of Tukey		
	Low	Medium	High	(P-value)	Low-Med	Low-High	Med-High
s01-36C	no data	1.30(.08)	1.36(.09)	< 0.01			
s02-36D	1.28(.09)	1.28(.10)	1.33(.10)	< 0.01	0.988	< 0.01	< 0.01
s03-36C	.92(.07)	.90(.08)	.97(.08)	< 0.01	0.128	< 0.01	< 0.01
s04-36C	1.24(.08)	1.33(.07)	1.29(.09)	< 0.01	< 0.01	< 0.01	< 0.01
s05-36C	1.34(.08)	1.36(.09)	1.35(.08)	0.232	0.201	0.606	0.732
s06-34D	1.26(.10)	1.28(.12)	1.39(.11)	< 0.01	0.390	< 0.01	< 0.01
s07-36C	1.20(.10)	1.20(.12)	1.10(.12)	< 0.01	0.979	< 0.01	< 0.01
s08-38D	1.19(.11)	1.20(.11)	1.24(.11)	0.007	0.952	0.011	0.025
s09-38D	1.24(.10)	1.16(.09)	1.14(.13)	< 0.01	< 0.01	< 0.01	0.613
s10-34C	no IP	no IP	no IP				
s11-34C	1.38(.12)	1.47(.12)	1.41(.11)	< 0.01	< 0.01	0.161	< 0.01
s12-36C	no IP	no IP	no IP				
s13-34D	1.25(.08)	1.23(.09)	1.36(.07)	< 0.01	0.257	< 0.01	< 0.01
s14-38C	1.17(.10)	no IP	1.19(.10)	0.077			
s15-34C	1.14(.11)	1.13(.10)	1.16(.10)	0.154	0.876	0.351	0.147
s16-34C	no IP	no IP	no IP				
s17-34C	1.77(.14)	1.72(.14)	1.72(.14)	0.001	0.020	0.630	< 0.01
Group Mean(SD)	1.27(0.19)	1.27(0.19)	1.29(0.19)	0.644			

2.3.4 Vertical Stiffness

Vertical stiffness means and standard deviations for each subject are displayed in Table 2-5. Vertical Stiffness (derived from the movement of the center of mass and force data) describes the vertical motions of the body and does not correspond to an actual spring in the model. Center of mass (COM) displacement during stance (a variable used in calculating vertical stiffness – Table 2-6) and sternum position (Table 2-7) were also calculated in order to help describe when vertical stiffness changes.

It was predicted that there would be a decrease in vertical stiffness with an increase in breast support. Nine out of 17 subjects experienced some decrease in vertical stiffness across support trials. Two subjects (s08, s09) experienced an increase in vertical stiffness with an increase in breast support. Two subjects (s04, s05) had no significant difference, and in four subjects (s07, s10, s13, s15) the results were unclear. Inter-subject analysis resulted in a p-value of .216 with two to three times the standard deviations of the intra-subject analyses. Repeated measures ANOVA was run on both COM and sternum position averages. Due to the highly individual results, there were no statistically significant differences ($p = .157$ and $p = .42$, respectively). Individual subject measurements (not statistically analyzed) showed a trend of increasing COM position as leg stiffness decreased. COM position was a major contributor to vertical stiffness. Many intra-subject sternum position measurements showed a greater overall difference between maximum and minimum trunk displacement while running as breast support increased and leg stiffness decreased.

Table 2-5. Vertical Stiffness means and standard deviations (normalized) for each subject.

Subject # and Size	Support Level				Significance of Tukey		
	Low	Medium	High	P-value	Low-Med	Low-High	Med-High
s01-36C	no data	40.9(3.3)	39.2(2.5)	< 0.01			
s02-36D	41.3(5.0)	37.4(4.2)	36.2(4.9)	< 0.01	< 0.01	< 0.01	0.189
s03-36C	53.7(4.6)	53.4(5.0)	48.0(5.2)	< 0.01	0.923	< 0.01	< 0.01
s04-36C	29.0(1.7)	29.0(1.6)	28.5(1.5)	0.034	1.000	0.060	0.061
s05-36C	39.9(3.4)	38.9(3.2)	39.1(2.6)	0.920	0.998	0.924	0.945
s06-34D	39.6(2.8)	38.9(3.0)	33.7(2.3)	< 0.01	0.216	< 0.01	< 0.01
s07-36C	29.9(1.9)	28.1(2.2)	29.3(2.4)	< 0.01	< 0.01	0.205	< 0.01
s08-38D	33.4(2.4)	37.3(2.5)	37.4(2.4)	< 0.01	< 0.01	< 0.01	0.885
s09-38D	27.0(2.5)	29.1(2.5)	30.5(2.8)	< 0.01	< 0.01	< 0.01	< 0.01
s10-34C	34.9(1.1)	33.1(1.1)	34.6(1.4)	< 0.01	< 0.01	0.262	< 0.01
s11-34C	34.3(1.6)	31.6(1.4)	32.3(1.4)	< 0.01	< 0.01	< 0.01	< 0.01
s12-36C	41.5(2.9)	36.3(2.8)	38.5(2.7)	< 0.01	< 0.01	< 0.01	< 0.01
s13-34D	48.1(3.3)	52.6(4.3)	49.1(3.5)	< 0.01	< 0.01	0.135	< 0.01
s14-38C	34.9(3.6)	35.8(3.0)	33.0(2.9)	< 0.01	0.155	< 0.01	< 0.01
s15-34C	32.9(2.8)	34.2(2.9)	32.7(2.5)	< 0.01	< 0.01	0.898	< 0.01
s16-34C	26.6(2.8)	25.1(2.0)	23.6(2.1)	< 0.01	< 0.01	< 0.01	< 0.01
s17-34C	29.6(1.6)	30.3(1.6)	29.4(1.9)	0.001	0.018	0.511	< 0.01
Group Mean(SD)	35.97(7.5)	35.68(7.9)	34.74(6.7)	0.216			

Table 2-6. Center of mass vertical displacement during stance. Mean (m) for each subject.

Subject # and Size	Support Level		
	Low	Medium	High
s01-36C	no data	0.048	0.050
s02-36D	0.051	0.053	0.054
s03-36C	0.031	0.031	0.036
s04-36C	0.067	0.069	0.069
s05-36C	0.050	0.051	0.051
s06-34D	0.042	0.042	0.053
s07-36C	0.068	0.069	0.064
s08-38D	0.062	0.059	0.058
s09-38D	0.070	0.066	0.061
s10-34C	0.066	0.066	0.064
s11-34C	0.050	0.058	0.056
s12-36C	0.043	0.055	0.051
s13-34D	0.031	0.029	0.032
s14-38C	0.059	0.058	0.062
s15-34C	0.053	0.049	0.052
s16-34C	0.079	0.083	0.092
s17-34C	0.079	0.075	0.086
Mean and SD (p = .157)	0.056(.015)	0.057(.015)	0.059(.015)

Table 2-7. Sternum Displacement mean values for each subject (mm).

Subject # Size	Support Level		
	Low	Medium	High
s01-36C	91.6	95.2	89.5
s02-36D	97.6	96.2	104.9
s03-36C	110.1	111.3	108.0
s04-36C	98.2	97.4	100.1
s05-36C	104.1	99.1	100.6
s06-34D	91.5	92.0	95.6
s07-36C	124.4	126.1	116.2
s08-38D	106.4	114.7	102.3
s09-38D	127.7	121.2	125.6
s10-34C	130.8	133.9	136.3
s11-34C	no data	93.2	93.3
s12-36C	86.5	92.4	75.3
s13-34D	75.0	76.9	87.8
s14-38C	104.3	102.2	109.2
s15-34C	75.6	72.1	79.9
s16-34C	115.2	103.8	128.2
s17-34C	120.1	137.9	143.6
Mean and SD (p = .42)	103.7(17.3)	104.5(18.7)	106.4(19.6)

2.3.5 Stride Frequency

Stride frequency results were unexpected. It was predicted that stride frequency would decrease with an increase in breast support, but the majority of responses were split between an increase and no significant difference. Only three subjects exhibited a decrease in stride frequency with an increase in breast support. Seven subjects had an increase in SF, and six subjects had no significant difference. Only one subject had an unclear pattern.

From a practical standpoint, all intra-subject mean values for all conditions were very similar. One might argue that the significance was inflated due to a large number of trials and small standard deviations, although some trends do seem to exist. Table 2-8 displays the means and standard deviations for stride frequency for each subject. The Inter-subject analysis revealed no significant differences ($p = .559$) and the variability was only slightly larger than the intra-subject analysis.

2.3.6 Results Summary

The general linear model repeated measures analysis resulted in probabilities of less than .01 for VBM, and .011 for active peak VGRF. The stride frequency, impact peak VGRF and vertical stiffness changes with support were not significant as expected. Tables 2-1 through 2-8 display the corresponding means and standard deviations. Individual differences varied greatly for each condition and single subject analysis proved to be a better mechanism for understanding adaptations in running kinetics which resulted from different breast support levels.

In summary, there were differences in responses between subjects for the variables tested and single subject analysis has shown trends in some variables. Table 2-9 summarizes the outcome for all variables and subjects for each individual subject.

Table 2-8. Stride Frequency means and standard deviations (Hz) for each subject.

Subject # and Size	Support Level				Significance of Tukey		
	Low	Medium	High	P-value	Low-Med	Low-High	Med-High
s01-36C	no data	1.41(.03)	1.40(.04)	0.070			
s02-36D	1.41(.04)	1.41(.05)	1.41(.04)	0.175	0.806	0.156	0.444
s03-36C	1.27(.03)	1.27(.02)	1.26(.03)	0.314	0.749	0.280	0.703
s04-36C	1.34(.03)	1.36(.04)	1.35(.04)	< 0.01	< 0.01	0.661	0.024
s05-36C	1.28(.03)	1.27(.03)	1.28(.03)	< 0.01	0.026	0.976	0.014
s06-34D	1.45(.03)	1.42(.03)	1.39(.04)	< 0.01	< 0.01	< 0.01	< 0.01
s07-36C	1.31(.04)	1.28(.04)	1.29(.04)	< 0.01	< 0.01	< 0.01	0.329
s08-38D	1.30(.05)	1.30(.05)	1.33(.06)	< 0.01	0.590	< 0.01	< 0.01
s09-38D	1.20(.04)	1.22(.03)	1.22(.03)	< 0.01	< 0.01	< 0.01	0.674
s10-34C	1.32(.02)	1.33(.03)	1.33(.03)	< 0.01	0.021	< 0.01	0.953
s11-34C	1.46(.04)	1.45(.03)	1.45(.03)	0.062	0.051	0.688	0.286
s12-36C	1.43(.03)	1.42(.04)	1.42(.03)	0.024	0.018	0.195	0.581
s13-34D	1.43(.03)	1.44(.03)	1.47(.03)	< 0.01	< 0.01	< 0.01	< 0.01
s14-38C	1.30(.05)	1.32(.03)	1.29(.04)	< 0.01	< 0.01	0.305	< 0.01
s15-34C	1.33(.05)	1.33(.03)	1.31(.04)	< 0.01	0.417	< 0.01	0.070
s16-34C	1.37(.05)	1.41(.08)	1.37(.06)	< 0.01	< 0.01	0.976	< 0.01
s17-34C	1.35(.07)	1.39(.06)	1.37(.09)	0.011	< 0.01	0.278	0.285
Group Means(SD)	1.35(0.07)	1.35(0.07)	1.35(0.07)	0.559			

Table 2-9. Summary of Single Subject analysis. Note that the outcomes are based on what happened as breast support increased from low to high.

Subject	Size	Vertical Breast Motion	Bra-Breast Stiffness	Vertical Stiffness	Active Peak	Impact Peak	Stride Frequency
Predicted		D		D	I	I	D
S01	36C	D	D	D	I	I	NSD
S03	36C	D	D	D	I	I	NSD
S04	36C	D	D	NSD	I	U	I
S05	36C	D	D	NSD	I	NSD	NSD
S06	34D	D	D	D	I	I	D
S07	36C	D	D	U	U	I	D
S10	34C	D	D	U	D	No IP	I
S11	34C	D	D	D	I	U	NSD
S15	34C	D	D	U	D	NSD	D
S17	34C	D	I	D	I	I	I
S02	36D	LMS	U	D	I	I	NSD
S08	38D	NSD (C1&C2)	D	I	NSD	NSD	I
S09	38D	LMS	D	I	I	D	I
S12	36C	NSD (C1&C2)	U	D	I	No IP	NSD
S13	34D	LMS	I	U	I	I	I
S14	38C	LMS	D	D	I	NSD	U
S16	34C	NSD (C2&C3)	D	D	D	No IP	I

Key

D = decrease

I = increase

U = unclear pattern

NSD = no significant difference between any conditions

No IP = no impact peak

LMS = low and medium (C1&C2) switch

2.4 Discussion

It has been clearly established that women who run with different levels of breast support experience changes in vertical breast motion, and that VBM differs with the size of breast (Eden, Valiant, Lawson, and Himmelsbach, 1992; Haycock, 1986; Lawson and Lorentzen, 1990; and Lorentzen and Lawson, 1987.) This study applies to a female population having bra sizes C and D and is specific to the low, medium, and high support sports bras used in testing. The magnitude of the outcome may differ with variation of breast size and level of support. Sports bras used in this study were the appropriate sizes for each subject, but breasts within the same size category may fit a bra differently.

This study investigated the relationship between levels of breast support and breast motion and how this changes running characteristics. One strength of this study was the design. Analyzing each subject for three different levels of breast support conditions allowed for inter-subject variability. By summarizing single subject results, it was possible to distinguish trends (Table 2-9).

In all 17 subjects, the high support condition allowed the least amount of breast motion. Thirteen of the 17 subjects showed a significant decrease in vertical breast motion with an increase in level of support that was consistent with the literature. The remaining four subjects, as described in the results section, may have had an excessive amount of breast motion in the low support bra that was not picked up by the MacReflex motion system. It might be necessary to have a different style of low support for the larger women that does not allow as much breast movement inside the bra.

The force data analyzed had multiple conclusions. An increase in breast support was associated with increased APGRF for 12 out of 17 subjects. It can be said that at least a trend exists between support and APGRF based on the results of the 17 individual single subject analyses.

When analyzing IPGRF, four of the runners did not have impact peaks at all, possibly due to being mid foot strikers. In the remaining subjects, there tended to be an increase in IPGRF with an increase in breast support. There was no significant change in four of the responses, a decrease in one, and two with unclear results. Impact peak appears to be a very individual characteristic.

A trend of decreasing vertical stiffness with an increase in breast support was found. While 4 of the subjects showed unclear results, 9 subjects showed a decrease in vertical stiffness with an increase in breast support. The lowest support condition resulted in the highest stiffness values in 10 of the subjects, even though a clear pattern was not always found as the support increased from low to medium to high. Since vertical stiffness equals the maximum force divided by the COM displacement, we can say vertical stiffness increased when the COM displacement decreased. Although the RMANOVA did not yield significant results, individual subjects showed a trend of decreased COM displacement during stance and decreased sternum movement when the vertical stiffness increased due to low breast support. When vertical stiffness decreased with the higher support conditions, individual subjects showed increasing COM displacement and increasing sternum motion.

Stride frequency yielded statistical differences, but all intra-subject mean values for all conditions were very similar. Stride frequency was predicted to decrease with higher breast support and decreased vertical stiffness, but most significantly different cases showed an increase in SF with higher breast support. One might conclude that there are only very small differences in stride frequency with a change in breast support.

The hypothesis stated that an increase in breast support should yield a decrease in VBM, vertical stiffness, and stride frequency and an increase in APGRF and IPGRF. In individual analysis, we found a decrease in VBM and vertical stiffness and an increase in APGRF. However, stride frequency showed equal number of subjects showing an increase or no change, and the changes were also very small. It is interesting that IPGRF changes seemed very individual, even when APGRF seemed to increase with support.

Our results support more investigation of APGRF, IPGRF, and vertical stiffness and the relationship to breast support. Further research might compare these characteristics in runners in a no-bra condition. This no-support condition may prove that women alter their running to compensate for discomfort when comparing no-, low-, and high support conditions. What might have added to the current study would be a perceived comfort level (maybe similar to a perceived level of exertion scale). Specific feedback from the subjects on their personal level of comfort in each condition might contribute to explaining running style changes.

It was found that women's running characteristics changed when they had diminished breast support. Demonstrating tangible compensations to running style and mechanical characteristics due to proper breast support may further promote the research and development of supportive sports bras for active women of all breast sizes. It is important to continue to improve sports bras that support both small and large breasted women and allow them to participate in exercise. Women will more likely remain motivated to exercise if they are comfortable and pain free. If women are able to exercise regularly, they will have the benefits of better health, more energy, less stress, and more confidence and self-esteem.

Chapter 3

Conclusions and Recommendations

It has been clearly established that women who run with different levels of breast support experience changes in vertical breast motion, and that VBM differs with the size of breast (Eden, Valiant, Lawson, and Himmelsbach, 1992; Haycock, 1986; Lawson and Lorentzen, 1990; and Lorentzen and Lawson, 1987.) Lorentzen and Lawson have demonstrated that excessive motion causes more pain for breast sizes C and D over sizes A and B (Lorentzen and Lawson, 1987).

In our group analysis, breast motion decreased while active peak vertical force increased with support; other kinetic and kinematic variables were unchanged for the group. Each subject had the least amount of vertical breast motion in the high support condition. Twelve of the 17 subjects had an increase in active peak VGRF with an increase in support while fewer (7) increased impact peak VGRF (not including four subjects with a midfoot strike pattern for whom no impact peak was evident). Vertical stiffness decreased for most subjects as breast support increased with 10 subjects having the greatest stiffness values at the lowest level of support. Similarly to vertical stiffness, COM displacement and sternum motion were very individual and did not yield significant RMANOVA results. Although group analysis did not yield significant results, individual subjects showed that both COM displacement and sternum motion increased with lower vertical stiffness and higher breast support. Finally, while there were significant changes in stride frequency for many subjects, the magnitude of the changes were relatively small compared to force and stiffness changes.

In summary, an increase in breast support has shown trends of decreasing vertical stiffness and increasing active peak and impact peak GRFs in the 17 subjects analyzed. Women adapt their running style enough that changes in running characteristics are evident when comparing bras that offer low, medium, and high support.

This study investigated the relationship between levels of breast support and breast motion and how this changes running characteristics. One strength of this study was the design. Previously, kinematic changes due to breast support were investigated using group analysis (Boschma, 1995). The large variations in the responses made it difficult to see any clear adaptation patterns, and the results did not show any significant differences in kinematics with changing support levels. In the current study, analyzing each subject as a single-subject for three different levels of breast support conditions allowed for inter-subject variability. It was possible to see which variables where highly individual like impact peak, and where adaptation trends existed, for example with ground reaction forces. Because of large inter-subject differences, it is important that future research designs consider individual adaptations to breast support.

Another strength of the study is the amount of data collected. By allowing the subject to get a stable running pattern first, and then collecting data for 40 seconds ensured a stable and repeatable characterization of the subject's running mechanics.

Further research might compare these characteristics in runners in a no-bra condition. This no-support condition may prove that women alter their running to compensate for discomfort when comparing no-, low-, and high-support conditions. This might have strengthened the trends detected by having a comparison to a "no support" condition.

Measuring perceived comfort level (perhaps similar to a perceived level of exertion scale) would have added to the study. Specific feedback from the subjects on their personal level of comfort in each condition might contribute to explaining running style changes.

Having a displacement criterion to categorize the sports bras as low, medium, and high support in addition to the criterion based on design would have ensured that, for example, a medium support bra for one subject was also a medium support for another subject. A design might include more than one bra for each support category, and low, medium, and high support is determined based on displacement. A medium support bra could be one that allows at least 10 mm less displacement than the low and 10 mm more than the high. Then the force data would be analyzed from the three bras that met those conditions.

Subject recruitment is also important. It may be beneficial to group subjects to one specific size (C separate from D instead of C and D together). It would be interesting to study how body composition and/or age affects comfort and running characteristics (for example, larger breasted women with low adipose vs. high adipose, and ages 25 vs. 45). Also, if IPGRF is to be studied, subjects should be pre-tested in order to ensure that they are rear-foot strikers when running on a treadmill.

Women of this study had decreased breast motion as breast support increased. In addition, many subjects had mechanical adaptations to increased support that included increased vertical ground reaction force but decreased vertical stiffness. The changes shown prove that some women alter how they run depending on the type of support a sports bra offers. Demonstrating tangible compensations to running characteristics due to improper breast support may further promote the research and development of supportive sports bras for active women of all breast sizes. If sports bras become more specialized in design towards larger breast sizes (as recommended by Lorentzen and Lawson, 1987), more women might be motivated to remain in a fitness program that might be uncomfortable with an unsupportive sports bra. It is also important to increase women's awareness of the availability of good sports bras at an affordable cost. If women are able to remain in an exercise program, the lifestyle benefits could include better health, less stress, and more confidence and self-esteem.

References

Barcikowski, R.S., and Robey, R.R. (1985). Sample size selection in single group repeated measures analysis. Paper presented at the annual meeting of the American Educational Research Association, Chicago, April 1985.

Boschma, A.L.C. (1995). Breast support for the active woman: Relationship to 3D kinematics of running. Master's thesis, Oregon State University, OR.

Carmack, C.L., Boudreaux, E., Amaral-Melendez, M., Brantley, P.J. and de Moor, C., 1999. Aerobic fitness and leisure physical activity as moderators of the stress-illness relation. Annals of Behavioral Medicine 21, 251-257.

Cavanagh, P.R., and LaFortune, M.A., 1980. Ground reaction forces in distance running. Journal of Biomechanics 13, 397-406.

Donatelle, R., Snow, C., and Wilcox, A., 1999. Wellness choices for health and fitness. Belmont, CA: Wadworth Pub Co.

Eden, K.B., Valiant, G.A., Lawson, L., and Himmelsbach, J., 1992. Three dimensional kinematic evaluation of sport bra design. Medicine and Science in Sport and Exercise 24(Suppl. 5), S187.

Fahey, T.D., Insel, P.M., and Roth, W.T., 1997. Fit and Well. MountainView, CA: Mayfield Pub Co.

Farley, C.T. and Gonzalez, O., 1996. Leg stiffness and stride frequency in human running. Journal of Biomechanics 29, 181-186.

Farley, C.T., Houdijk, H.H.P., van Strien, C., and Louie, M., 1998. Mechanism of leg stiffness adjustment for hopping on surfaces of different stiffnesses. Journal of Applied Physiology 85, 1044-1055.

Ferris, D.P. and Farley C.T., 1997. Interaction of leg stiffness and surface stiffness during human hopping. Journal of Applied Physiology 82, 15-22.

Ferris, D.P., Louie, M., Farley, C.T., 1998. Running in the real world: Adjusting leg stiffness for different surfaces. Proceedings of the Royal Society of London 7, 989-994.

Fewster, J.B. (1996) The role of musculoskeletal forces in the human walk-run transition. Master's thesis, Oregon State University, OR.

Hassmen, P., Koivula, N. and Uutela, A. (2000). Physical exercise and psychological well-being; a population study in Finland. Preventive Medicine 30(1), 17-25.

Haycock, C., 1986. Women in sports. In: Vinger, P.F., Hoerner, E.F. (Eds.), Sports Injuries: The unthwarted epidemic (2^{nd} ed.). Littleton, MA, pp. 77-80.

Haycock, C.E., 1978. Breast support and protection in the female athlete. AAHPERD Research Consortium Symposium papers, Vol. 1, Book 2 pp. 50-53. Reston, VA.

Heise, G.D. and Martin P.E., 1998. "Leg Spring" characteristics and the aerobic demand of running. Medicine and Science in Sports and Exercise 30, 750-754.

Hunter, I. (2001). The Effect of a Near-Maximal Effort One-Hour Run on Preferred and Optimal Stride Rate and Vertical Stiffness, Unpublished doctoral dissertation, Oregon State University, OR.

Kram, R., Griffin, T.M., Donelan, J.M., and Chang, Y.H., 1998. Force treadmill for measuring vertical and horizontal ground reaction forces. Journal of Applied Physiology 85, 764-769.

Kram, R. and Powell, J., 1989. A treadmill-mounted force platform. Journal of Applied Physiology 67, 1692-1698.

Lawson, L. and Lorentzen, D., 1990. Selected sports bras: Comparisons of comfort and support. Clothing and Textiles Research Journal 8, 55-60.

Lorentzen, D., and Lawson, L., 1987. Selected sports bras: A biomechanical analysis of breast motion while jogging. The Physician and Sports Medicine 15, 128-139.

MacReflex Version 3.0, 1995. Glastonburg, CT: Qualisys, Inc.

Mason, B.R., Page, K., and Fallon, K., 1999. An analysis of movement and discomfort of the female breast during exercise and the effects of breast support in three cases. Journal of Science and Medicine in Sport 2, 134-144.

McMahon, T.A., Cheng, G.C., 1990. The mechanics of running: How does stiffness couple with speed? Journal of Biomechanics 23 (suppl. 1), 65-78.

Miller, D.I., 1990. Ground reaction forces in distance running. In: Cavanagh, P.R. (Ed.), Biomechanics of Distance Running. Champaign, IL, pp. 203-223.

Munro, C.F., Miller, D.I., and Fuglevand, A.J., 1987. Ground reaction forces in running: a reexamination. Journal of Biomechanics 20, 147-155.

Appendices

Appendix A - Literature Review

In order to further study the effectiveness of sports bras, it was important to explore a relationship between breast support (defined by amount of breast motion) and its affect on running kinematics and kinetics. Current research reports how breast motion varies due to different levels of support during running. There are no published studies that compare running kinetics for different amounts of breast motion. A detailed analysis of running characteristics is required to understand how running is affected by breast motion. The following review of literature addresses ground reaction forces (GRF) and vertical stiffness as studied in running, overground vs. treadmill running, the use of the OSU instrumented treadmill for force data collection, and biomechanical studies of breast motion.

Ground Reaction Forces

Factors affecting gait during running include running speed, stance time, and stride frequency. These factors also affect vertical GRFs. Ground reaction forces represent the force the ground exerts on the foot and is transmitted through the body. It has been reported that an increase in running speed is associated with increases in active and impact peak vertical GRFs and average vertical GRF (Miller, 1990; Munro, Miller, and Fuglevand, 1987). At a speed of 3 m/s, Miller (1990) reported an average vertical GRF of 1.4 times body weight (1.4 BW), a stance time of 270 ms, and active peak of 2.51 BW. Munro et al. (1987) increased running speed from 2.5 to 5.5 m/s and reported an increase of impact force from 1.57 BW to 2.3 BW and an increase in average vertical GRF from 1.4 BW to 1.7 BW. At a higher speed such as 4.5 m/s, the average vertical GRF has been reported as 2.8 BW (Cavanagh and LaFortune, 1980). In the current study where speed was kept constant, other factors such as breast support may have contributed to any changes in VGRF.

Leg Stiffness and Vertical Stiffness

Leg stiffness refers to the stiffness of the leg in contact with the ground and vertical stiffness describes the vertical motions of the body and does not correspond to an actual spring in the model (Heise and Martin, 1998). Leg stiffness and vertical stiffness in both hopping and running have been shown to change due to surface stiffness, stride frequencies, foot strike position, and foot orientations. An increase in surface stiffness has been repeatedly proven to cause a decrease in leg stiffness in both hopping and running (Farley, Houdijk, van Strien, and Louie, 1998; Ferris, Louie, and Farley, 1998; Ferris and Farley, 1997). However, when surface stiffness is kept constant, a change in stride frequency or stance time affects leg and vertical stiffness of the runner. Farley and Gonzalez (1996) varied stride frequency from 26% below each subject's natural stride frequency to 36% above each subject's natural stride frequency. Changing stride frequencies alters the angle swept by the leg, which results in a change in leg stiffness. Leg stiffness varied from 15.1 kN/m at the lowest frequency to 52.4 kN/m at the highest frequency (Farley and Gonzalez, 1996). In addition to an increase in leg stiffness with increased stride frequency, there was also a decrease in vertical GRF, decrease in stance time, and a decrease in the magnitude of vertical displacement of the COM that resulted in an increase in vertical stiffness.

Treadmill and Overground Running

The use of a force treadmill has been supported as an effective means of data collection in the laboratory. Kram and Powell (1989) and Kram, Griffin, Donelan, and Chang (1998) supported use of an instrumented treadmill because it can save time in data collection, laboratory space, and it is possible to collect successive running and walking steps.

Force Treadmill

The OSU treadmill used in this experiment was a Quinton Model Q55 treadmill previously instrumented with 6 piezoelectric force transducers (PCB Piezotronics 208A03 and 208A02) embedded under the treadmill belt at the front, middle and back of the treadmill bed on both left and right sides (Fewster, 1996). Steps were taken by Fewster to reduce treadmill bed flexing by placing transducers at the corners as well as middle of the bed, thus increasing rigidity. The motor unit was detached from the treadmill bed except for the drive belt thus minimizing vibration from the motor to the bed and the transducers. The natural frequency of the treadmill during the initial placement was measured at 275 Hz. Since then, Fewster's recommendations have been followed and the treadmill has been permanently fixed to the floor of the Biomechanics Laboratory in the basement, and the resonant frequency is ~100 Hz. The following reliability and validity report was summarized from Jonathan Fewster's Masters thesis, Appendix C (Fewster, 1996).

In order to validate the treadmill, Fewster (1996) performed various tests. The first test evaluated the treadmill's ability to measure applied static loads. Weights were stacked in a precise location, measured, removed, and re-measured. This procedure was repeated and an average error of 26.56 N was found for known forces ranging from 221.47 N (average errror 21.37 n) to 134.64 N (average error 39.21 N). The second test validated the treadmill's ability to measure VGRFs against a floor-mounted force plate. Data were collected on individuals running at various speeds across the force plate and on the treadmill. Correlation between treadmill and force plate were made between various measurements, the least similar with an r = 0.7257 for rise rates calculated from the peak impact force and the highest correlation was a measure of total impulse with r = 0.9838. The results showed some differences between treadmill and force plate recordings that were reported as being possibly due to the accuracy of the treadmill, overground vs. treadmill running, and subject trial-to-trial variability (Fewster, 1996). Overall, the results were acceptable.

Another test was done to validate the treadmill's measure of center of pressure for both static and dynamic loads. For static testing, a point mass was applied at a known location with and without the belt moving. The calculated values were "reasonably good" but not accurate enough to perform inverse dynamics.

Repeated testing was done to see how accurately the treadmill measured body weight moving along the belt. Subjects stood in one place and were moved along the belt from the front to the rear of the treadmill. This was repeated. The treadmill proved to be precise in measuring the body weight as it moved from front to back, but had a lower accuracy of the actual body weight measurement. Overall, it was reported that the treadmill displayed sufficient validity in this area. The ability to calculate body weight was measured by having subjects standing or walking on the treadmill. When a comparison between static and walking measures was made, error ranged from 1.96% at the low speed to 5.54% at a high speed. The force values were consistent but relatively large, but were easily comparable to each other, thus reliable.

In order to validate dynamic force measurements, a force hammer (hammer with a force transducer) was applied to the middle of the treadmill belt and the curves from the treadmill and force hammer were compared. The correlation between the force treadmill and hammer measurements showed $r^2 = 0.9996$ to 0.9998 as weight increased to 250 N. Finally, repeatability was tested. Two subjects ran and walked on the treadmill for each of 4 speeds. This was repeated three times within a day, with the force transducers and treadmill shut off and reset in between trials. Most variability was small, 1-4% of average force, which was found to be acceptable.

In summary, Fewster provided evidence that the OSU instrumented treadmill was valid for static and dynamic loads. Average errors were approximately 30 N.

Breast Motion

The need for wearing sports bras has been well established and many authors have found breast pain linked to excessive breast motion while running (Eden, Valiant, Lawson, and Himmelsbach, 1992; Haycock, 1986; and Lawson and Lorentzen, 1990). It has also been established that different sports bra styles result in different amounts of vertical breast motion (Eden et al., 1992; Haycock, 1986; and Lawson and Lorentzen, 1990). The following summary describes breast motion kinematics under various levels of breast support and how breast motion affects comfort.

Lorentzen and Lawson (1987) evaluated eight different sports bras to determine the biomechanical support provided to women of breast sizes A, B, C, and D. They also evaluated breast motion under nude conditions and supported the idea that vertical displacement could be a problem especially for larger breasted women, and sports bras need to be designed specifically for the D sizes. The research showed that excessive motion caused more breast pain for C and D sizes over A and B sizes (Lorentzen and Lawson, 1987).

Another study by Lawson and Lorentzen (1990) analyzed sports bra support of small, medium, and large breasted women, but in addition, they studied the relationship between the subjective comfort measures and the quantitative findings. They found a significant relationship between comfort and support for five of the sports bra designs. A significant correlation between comfort and quantitative displacement was only found with two styles. The researchers suggested that perception of support has more basis than restriction of vertical motion. They concluded that smaller breasted women find "comfort" with less restricting models, while larger breasted women need control of breast displacement on all sides in order to have pain-free exercise (Lawson and Lorentzen, 1990).

Currently, there have not been any studies reporting statistical or practical significance in kinetic changes while running with various levels if breast support. Boschma (1995) studied kinematic changes with breast sizes B, C, and D for moderate and full breast support for 15 subjects. There were no statistically significant differences between support levels for stride length, stride rate, vertical trunk displacement, and arm range of motion even though there were significant differences in vertical breast displacement due to the level of support (Boschma, 1995). In the current study, we used a design with multiple single-subject analyses which made it possible to detect significant changes in kinetic variables due to increasing breast support on a case by case basis in order to detect population trends.

In summary, excessive breast motion causes pain in larger breasted women. There have been many studies showing how changes in running characteristics such as running speed and stride frequency can also affect vertical stiffness and vertical GRFs. Women who are experiencing discomfort during running may alter their gait in an attempt to decrease pain or discomfort, and their accommodations may be quantifiable by measuring changes in stride frequency, vertical GRFs, and vertical stiffness.

Appendix B - IRB Proposal

HUMAN SUBJECTS REVIEW:

ADAPTATION OF VERTICAL GROUND REACTION FORCE DUE TO CHANGES IN BREAST SUPPORT IN RUNNING

This study is based on work that was previously approved by the IRB in September 1992 and re-approved each year since then. The testing will follow similar procedures for breast motion data collection with the addition of force data collection via a treadmill.

SIGNIFICANCE:
For women participating in exercise, breast support is crucial. Without adequate breast support, women often find exercise to be uncomfortable and may alter their running pattern in attempt to reduce breast motion. Such adaptations are likely to affect kinematic and kinetic characteristics and affect exercise enthusiasm and performance.

METHODS:
Subjects will run on a treadmill at a 10-minute per mile pace for a short duration (less than 2 minutes) for each of three sports bra support conditions. During each run, motion analysis methods will be used to characterize the frontal plane motion of the breast for low, medium and high support sports bra designs. Motion characteristics such as displacement, velocity and acceleration of the breast with respect to the trunk will be determined from the motion analysis records. Simultaneously, vertical ground reaction force will be collected from the treadmill. Force characteristics such as peak vertical force and impulse will be determined for each stride during the brief recording period.

The force measurement process will not require any unusual apparatus or procedures for the subjects. The treadmill has been instrumented with force transducers and the output will be monitored via an adjacent computer.

SUBJECTS:
Between 20-25 females will be recruited for this study. Requirements for participation include participation in any exercise activity at least once per week, the ability to run at 6 miles per hour, and being the appropriate size for the study (bra sizes of 36-42 inch C or D cup).

RISKS AND BENEFITS:
Participation in this study carries minimal risk. The subjects will be asked to run at a moderate pace for a short duration of time. They will be instructed on the use of a

treadmill and given adequate amount of time to familiarize themselves to running on it. The low intensity and short duration make the risk of serious health problems very low.

The results of the study will support the importance of appropriate sports bra support when participating in exercise. A complimentary sports bra will be given to all participants.

CONFIDENTIALITY:

The identity of subjects will remain confidential during data acquisition, analysis, and reporting of results. All subject identification will be numerical and held confidential. Data collection will be performed in a secured location in the Biomechanics Lab where the subjects' privacy will be maintained. The motion analysis methods involve tracking reflective markers on the subject and not physical images. These are saved as simple numeric data files without video tape recording. Hence, subject identity and confidentiality will not be at risk after data collection. Subjects' participation in the study will be confidential because the researcher will be contacted through personal email or at home.

Appendix C - Consent Form

CONSENT FORM

TITLE: Adaptation of Vertical Ground Reaction Force due to Changes in Breast Support in Running

INVESTIGATOR: Gerald Smith, Ph.D. and Nicole Robert

PURPOSE: The purpose of this study is to determine if vertical ground reaction forces (forces generated by the foot when contacting the ground) change with varying sports bra support during treadmill running.

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

All testing will be conducted in the Biomechanics and Human Performance Laboratories in the Women's Building at Oregon State University. As a subject, I will report to the test site for the following procedures:

1. Body measurements. My height, weight, leg length, and chest circumference will be measured and my age made known.

2. Biomechanical data collection. My upper body motion will be recorded from the frontal view while I am jogging on a flat motorized treadmill at a 10 minutes per mile (6 miles per hour) pace. While I am jogging the treadmill will record the force data from my feet reacting with the treadmill. I will be recorded for approximately 2 minutes for each of the three different sports bra support styles. Testing will be done in a secured location in the Biomechanics Laboratory by female researchers.

3. I understand that the risks associated with participation are minimal. Running may be associated with muscle soreness, but at the moderate speed and short duration of the running in this study, such effects should be mild. Coronary complications such as chest pain and irregular heartbeats have occasionally been associated with vigorous exercise. However, based on my fitness and the low exercise intensity, it is unlikely such problems will occur. I participate in active sports or exercise, such as running and step aerobics, at least once per week.

I will be given instruction and practice for jogging on a treadmill. My identity will be kept confidential and will not be used in any way in the publication or presentation of findings of this investigation. All data collections will be done in a secured room by female researchers.

The benefits of my participation in this study include contributing to scientific study of sports bras, which will increase awareness of the importance of adequate support during exercise. I will also receive a complimentary sports bra in return for my participation.

I understand my participation includes I laboratory session requiring approximately 45 minutes.

I understand that the University does not provide a research subject with compensation or medical treatment in the event that the subject is injured as a result of participation in the research project.

I have been completely informed about and understand the nature and purpose of this research. The researcher has offered to answer any further questions I may have. I understand that my participation in this study is completely voluntary and that I may refuse to participate or withdraw from the study at any time without penalty or loss of benefits to which I am otherwise entitled. I understand that if I withdraw from the study before it is completed, I will no longer receive the complimentary sports bra I am otherwise entitled to.

If any questions should arise during my participation in this research project, I am to call Nicole Robert at (541) 346-7619 or (541) 737-5933 or Gerald Smith at (541) 737-5928. All other questions should be directed to Mary Nunn, Sponsored Programs Officer, OSU Research Office, (541) 737-0670.

I have read this contract and agree to participate in this study.

______________________ ____________

Subject's Signature Date

____

Subject's Printed Name

______________________ ____________

Investigator's Signature Date

Appendix D - Matlab Program for Breast Motion Data Analysis

The following program was written in Matlab and used to analyze breast motion.

```
%     filename: bmotion.m
%     author: Nicole Shivitz
%     date: 14 Feb 2000
%
% bmotion.m reads in a .csv file and lets the user choose max and min values then
% calculates  the difference and saves them to a .txt file.
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Settings

clear
fclose('all');
cd d:\nicole\Jogbra\Motion\Data\d

ctime=40;        % input('Enter time in sec that collected data for: ');
sfrq=120;        % input('What is the force treadmill sampling frequency in Hz? ');

noch=6;          % input ('Enter number of variables in file: ');
tme=1/sfrq;      % time increment to then determine ms


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Opening the MacReflex *.csv file


Kinefile=input('Enter motion .csv data filename : ','s');
subj = Kinefile(:,(length(Kinefile)-10):(length(Kinefile)-6));
tr = Kinefile(:,(length(Kinefile)-5):(length(Kinefile)-4));
datinfile = [subj, tr '.csv'];
datoutfile = [subj, tr '.cms'];
cd (subj);

% Reading the MacReflex experimental input file

kinedat = csvread(datinfile);
if kinedat == -1
  'File could not be opened'
```

```
 return
end

NumSamples = size(kinedat,1);        % finds the number of samples in the data set


% Find vertical motion

Mvert = (kinedat(:,3)) - (kinedat(:,6));

ff=[(1:5000),1];
framenum=ff';

% Information for all buttons (for manual onset choosing)
        top=0.95;
        bottom=0.05;
        left=0.82;
        yInitLabelPos=0.90;
        btnWid = 0.13;
        btnHt=0.08;

        % Spacing between the label and the button for the same command
        btnOffset=0.02;

        % Spacing between the button and the next command's label
        spacing=0.02;

% Create individual step matrix

Endg = 300;
Startg = 1;
count=1;
count2=0
global newstab;

% Enter parameters

for i = 1:60
     while Startg <= 4740

     figure
     plot (framenum(Startg:Endg),Mvert(Startg:Endg),'c')
     hold on
     k=menu('Is the last curve acceptable?', 'Yes', 'No');

     if k==1
```

```
        hold on
        count = count2 + 1;
        count2 = count + 19;

        zoom
        pause

zoom off
[x,y]=ginput(20);

newstab(1,1)=(y(1));
newstab(1,2)=(y(2));
newstab(1,3)=(y(3));
newstab(1,4)=(y(4));
newstab(1,5)=(y(5));
newstab(1,6)=(y(6));
newstab(1,7)=(y(7));
newstab(1,8)=(y(8));
newstab(1,9)=(y(9));
newstab(1,10)=(y(10));
newstab(1,11)=(y(11));
newstab(1,12)=(y(12));
newstab(1,13)=(y(13));
newstab(1,14)=(y(14));
newstab(1,15)=(y(15));
newstab(1,16)=(y(16));
newstab(1,17)=(y(17));
newstab(1,18)=(y(18));
newstab(1,19)=(y(19));
newstab(1,20)=(y(20));

        bmax=newstab;

        zoom
        pause

zoom off
[x,y]=ginput(20);

newstab(1,1)=(y(1));
newstab(1,2)=(y(2));
newstab(1,3)=(y(3));
newstab(1,4)=(y(4));
newstab(1,5)=(y(5));
newstab(1,6)=(y(6));
newstab(1,7)=(y(7));
```

```
        newstab(1,8)=(y(8));
        newstab(1,9)=(y(9));
        newstab(1,10)=(y(10));
        newstab(1,11)=(y(11));
        newstab(1,12)=(y(12));
        newstab(1,13)=(y(13));
        newstab(1,14)=(y(14));
        newstab(1,15)=(y(15));
        newstab(1,16)=(y(16));
        newstab(1,17)=(y(17));
        newstab(1,18)=(y(18));
        newstab(1,19)=(y(19));
        newstab(1,20)=(y(20));
                pause

                bmin=newstab;

                % Find vertical motion
                vertmot=bmax-bmin;

                % save variables to output matrix
                format short e;
                Forcematrix(1,1:count2) =  1:count2;
                Forcematrix(2,count:count2) = bmax;
                Forcematrix(3,count:count2) = bmin;
                Forcematrix(4,count:count2) = vertmot;

                Startg = Endg + 1;
                Endg  = Startg + 300;
                k==2;
                close all

        else
        Endgstr=input('Enter endpoint : ','s');
                Endg = str2num(Endgstr);
        end
        end
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Create the output file to be used as the statistical program's input file
  disp(['Creating output data file ', datoutfile,' ...']);

     fid = fopen(datoutfile, 'w+');
```

```
        fprintf(fid,'%-12s\t %-12s\t %-12s\t %-12s\n ','Number','Breast max',...
        'Breast min','Vertical Disp (mm)');
        fprintf(fid, '%8.6f\t%8.6f\t%8.6f\t%8.6f\n', Forcematrix);
        fclose(fid);
        disp(['                    Done  (', num2str(toc), ')']);

figure
title('The program has finished calculating - Press any key to close all graphs');
pause
close all
```

Appendix E - Matlab Program for Force Data Analysis

The following program was written in Matlab and used to analyze breast motion.

```
%       filename: forcestep.m
%       author: Nicole Shivitz
%       date: 12 Jan 2000
%
% Forcestep.m is a script file, which takes the output from the OSU instrumented force
% treadmill (.txt) and converts it to vertical ground reaction forces. Then leg stiffness,
% stance time, peak VGRF and impact VGRF are calculated and saved to an output file.
% The program uses thirty newtons as a cutoff for heel strike and toe off based
% on literature. The user may choose to override computer pick if necessary.
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Settings

clear
fclose('all');
cd d:\nicole\Jogbra\Force

ctime=40;       % input('Enter time in sec that collected data for: ');
sfrq=500;       % input('What is the force treadmill sampling frequency in Hz? ');
cfrqA=60;       % input('What Vertical Force filter cutoff frequency do you want? ');

noch=6;         % input ('Enter number of variables in file: ');
tme=1/sfrq;     % time increment to then determine ms
colordef none

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Opening the force *.txt file

Forcefile=input('Enter force .txt data filename : ','s');
subj = Forcefile(:,(length(Forcefile)-10):length(Forcefile)-7);
tr = Forcefile(:,(length(Forcefile)-6):length(Forcefile)-4);
Forceinfile = [subj, tr '.txt'];
Forceoutfile = [subj, tr '.cms'];
cd (subj);

% Reading the Peak experimental input file
```

```
Force = csvread(Forceinfile);
if Force == -1
  'File could not be opened'
  return
end

NumSamples = size(Force,1);% finds the number of samples in the data set

% Assigning transducers:
t1= Force (:,1);
t2= Force (:,2);
t3= Force (:,3);
t4= Force (:,4);
t5= Force (:,5);
t6= Force (:,6);

% Assigning Scaling Factors
s1 = .01041;
s2 = .01019;
s3 = .01033;
s4 = .01022;
s5 = .0521;
s6 = .0533;

%%%%%%%%%%%%%%%%%%%%%%%%%% Convert volts to Newtons of Force

F1 = (((t1 - 2048)/409.6)/s1)*4.4482;
F2 = (((t2 - 2048)/409.6)/s2)*4.4482;
F3 = (((t3 - 2048)/409.6)/s3)*4.4482;
F4 = (((t4 - 2048)/409.6)/s4)*4.4482;
F5 = (((t5 - 2048)/409.6)/s5)*4.4482;
F6 = (((t6 - 2048)/409.6)/s6)*4.4482;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Filtering the Force data
% 4th order low-pass

sfrqA=sfrq./2;
cfrqA=cfrqA/.802;
wnA=cfrqA/sfrqA;
filterOrder = 4;

[B,A]=butter(filterOrder,wnA);

 smooth(:,1)=filtfilt(B,A,F1);
```

```
  smooth(:,2)=filtfilt(B,A,F2);
  smooth(:,3)=filtfilt(B,A,F3);
  smooth(:,4)=filtfilt(B,A,F4);
  smooth(:,5)=filtfilt(B,A,F5);
  smooth(:,6)=filtfilt(B,A,F6);

  FTot = smooth(:,1) + smooth(:,2) + smooth (:,3) + smooth (:,4)+ smooth (:,5)+ smooth
(:,6);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% FTot = F1 + F2 + F3 + F4 + F5 + F6;

ff=[(1:20000),1];
framenum=ff';

% Information for all buttons (for manual onset choosing)
        top=0.95;
        bottom=0.05;
        left=0.82;
        yInitLabelPos=0.90;
        btnWid = 0.13;
        btnHt=0.08;

        % Spacing between the label and the button for the same command
        btnOffset=0.02;

        % Spacing between the button and the next command's label
        spacing=0.02;

% Create individual step matrix

Endg = 1000;
Startg = 1;
count=0;
fltstep=0;
global newstab;
global ystab;

% Enter parameters

wtstr=input('Enter subject mass in kilos : ','s');
wt=str2num(wtstr);
legstr=input('Enter subject leg length in meters : ','s');
legl=str2num(legstr);
```

```
for i = 1:40
        while Startg <= 19000

        figure
        plot (framenum(Startg:Endg),FTot(Startg:Endg),'c')
        hold on
        k=menu('Is the last curve acceptable?', 'Yes', 'No');

        if k==1

                l=ones(20000,1);
                bline=30*(l(Startg:Endg));
                plot(framenum(Startg:Endg),bline, 'r')
                zoom
                hold on

                count = count + 1;


                % The Start button (for manual curve start choosing)
           uicontrol( ...
        'Style','push', ...
              'Units','normalized', ...
              'Position',[left bottom+btnHt+spacing+btnHt+spacing  btnWid btnHt], ...
              'String','Startstep', ...
              'Callback','getst');

                pause
                 startstep=round(newstab);
                 flt=startstep-fltstep;
                 flight=tme*flt;

                % The End button (for manual curve start choosing)
           uicontrol( ...
        'Style','push', ...
              'Units','normalized', ...
              'Position',[left bottom+btnHt+spacing+btnHt+spacing  btnWid btnHt], ...
              'String','Endstep', ...
              'Callback','getst');

                pause

                endstep=round(newstab);
                fltstep=endstep;
                % Find stance time(sec)
```

```
        st=endstep-startstep;
        stance=tme*st;

        % Active Peak VGRF
        PGRF=max(FTot(startstep:endstep));
        plot(PGRF, 'r+')
        normPGRF=PGRF/(wt*9.81);

        % Impact Peak GRF
        % The End button (for manual curve start choosing)
    uicontrol( ...
  'Style','push', ...
      'Units','normalized', ...
      'Position',[left bottom+btnHt+spacing+btnHt+spacing  btnWid btnHt], ...
      'String','Impact Peak', ...
      'Callback','getst');

        pause

        xMGRF=round(newstab);
        MGRF=FTot(xMGRF,1);
        plot(MGRF, 'b+')
        normMGRF=MGRF/(wt*9.81);


        strrate = 2*(stance + flight);  % stride rate
        strvel=2.86;                    % Velocity of treadmill in m/sec
        strlength = strvel * strrate; % stride length
        strfreq=1/strrate;              % stride frequency

%%%%%%%%%%%%%%%%%% Calculate Leg Stiffness

        % Create a COM acceleration Matrix
        COMacc =((FTot(startstep:endstep)-(wt*9.81))/wt);

        % Find COM velocity
        [COMaccMax,posmax]=max(COMacc);
        tend=length(COMacc);
        Vi=0;
        COMcount=1;
        Ai=posmax;
        for  Time = posmax:tend
                Vf=(Vi + ((COMacc(Ai))*0.002));
                Vi=Vf;
                Ai=Ai+1;
                COMcount = COMcount + 1;
```

```
            absVf=abs(Vf);
            if Vf==absVf
                    COMvel(COMcount,1)=Vf;
            else
                    Time=tend;
            end
    end

    % Find COM position
    time_count=(length(COMvel)-1)*.002;
    time_line=(0:0.002:time_count);
    COMpos=trapz(time_line,COMvel);
    ang=asin((2.68*stance)/(2*legl));
    Kleg = (PGRF/(COMpos + (legl*(1-cos(ang)))))*(legl/(wt*9.81));
    Kvert = (PGRF / COMpos)*(legl/(wt*9.81));

    % save variables to output matrix
    format short e;
    Forcematrix(1,count) = count;
    Forcematrix(2,count) = startstep;
    Forcematrix(3,count) = endstep;
    Forcematrix(4,count) = stance;
    Forcematrix(5,count) = normPGRF;
    Forcematrix(6,count) = normMGRF;
    Forcematrix(7,count) = COMpos;
    Forcematrix(8,count) = Kleg;
    Forcematrix(9,count) = Kvert;
    Forcematrix(10,count) = strlength;
    Forcematrix(11,count) = strfreq;


    % Check for next curve on graph
    a=input('Is there another curve in this set?(y/n) : ','s');
    if a=='y'
            %repeat choosing start and end

  else
            Startg = Endg + 1;
            Endg  = Startg + 1000;
            k==2;
            close all
    end

else
Endgstr=input('Enter endpoint : ','s');
    Endg = str2num(Endgstr);
```

```
        end
        end
end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Create the output file to be used as the statistical program's input file
  disp(['Creating output data file ', Forceoutfile,' ...']);

      fid = fopen(Forceoutfile, 'w+');

         fprintf(fid,'%-12s\t %-12s\t %-12s\t %-12s\t %-12s\t %-12s\t %-12s\t %-12s\t %-
12s\t %-12s\t %-12s\n','Step #','Start frame',...
         'End frame','Stance time(sec)','APGRF(BW)','IPGRF(BW)', 'COMpos(m)',
'Kleg(norm)','Kvert(norm)','stride length(m)', 'stride frequency(1/sec)');
         fprintf(fid,
'%8.6f\t%8.6f\t%8.6f\t%8.6f\t%8.6f\t%8.6f\t%8.6f\t%8.6f\t%8.6f\t%8.6f\t%8.6f\n',
Forcematrix);
         fclose(fid);
 figure
title('The program has finished calculating - Press any key to close all graphs');
pause
close all
```

Appendix F - Individual Single-Subject Results Tables

S01	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	23.55 (2.1)	1.98	4.62	No data	No data	No data	No data
C2	19.62 (2.1)	1.85	3.60	40.94 (3.28)	1.91 (.07)	1.30 (.08)	1.41 (.03)
C3	17.01 (2.0)	1.63	2.72	39.18 (2.49)	1.96 (.06)	1.36 (.09)	1.40 (.04)

S02	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	69.76 (7.46)	2.24	15.52	41.30 (4.99)	1.84 (.04)	1.28 (.09)	1.41 (.04)
C2	76.85 (5.49)	2.64	20.18	37.35 (4.20)	1.96 (.05)	1.28 (.10)	1.41 (.05)
C3	51.55 (4.34)	2.01	10.19	36.20 (4.92)	1.98 (.05)	1.33 (.10)	1.41 (.04)

S03	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	76.91 (.47)	1.99	15.24	53.68 (4.59)	1.75 (.04)	.92 (.07)	1.27 (.03)
C2	69.29 (.47)	1.95	13.45	53.42 (5.0)	1.77 (.04)	.90 (.08)	1.27 (.02)
C3	45.50 (.47)	1.35	6.05	48.03 (5.24)	1.83 (.04)	.97 (.08)	1.26 (.03)

S04							
	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	48.62 (2.95)	1.67	8.07	28.99 (1.72)	1.96 (.04)	1.24 (.08)	1.34 (.03)
C2	37.43 (3.62)	1.68	6.22	28.99 (1.58)	2.01 (.04)	1.33 (.07)	1.36 (.04)
C3	21.37 (3.73)	1.39	2.87	28.45 (1.48)	2.02 (.03)	1.29 (.09)	1.35 (.04)

S05							
	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	33.25 (5.96)	1.79	5.74	38.89 (3.41)	1.93 (.04)	1.34 (.08)	1.28 (.03)
C2	27.72 (5.50)	1.69	4.48	38.92 (3.19)	1.98 (.04)	1.36 (.09)	1.27 (.03)
C3	22.18 (6.49)	1.32	2.67	39.07 (2.56)	1.97 (.04)	1.35 (.08)	1.28 (.03)

S06							
	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	48.46 (5.21)	2.36	11.31	39.57 (2.80)	1.90 (.04)	1.26 (.10)	1.45 (.03)
C2	44.48 (5.49)	2.09	9.17	38.89 (3.02)	1.92 (.05)	1.28 (.12)	1.42 (.03)
C3	28.99 (3.25)	1.86	5.32	33.72 (2.27)	1.99 (.04)	1.39 (.11)	1.39 (.04)

S07	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	50.35 (6.44)	1.83	9.06	29.87 (1.91)	2.09 (.07)	1.20 (.10)	1.31 (.04)
C2	44.63 (5.69)	1.72	7.55	28.08 (2.22)	2.21 (.08)	1.20 (.12)	1.28 (.04)
C3	29.33 (4.90)	1.28	3.63	29.32 (2.42)	2.10 (.07)	1.20 (.12)	1.29 (.04)

S08	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	67.96 (7.68)	1.83	12.28	33.43 (2.42)	2.01 (.07)	1.19 (.11)	1.30 (.05)
C2	69.57 (6.71)	1.67	11.48	37.27 (2.48)	2.02 (.07)	1.20 (.11)	1.30 (.05)
C3	41.00 (6.87)	1.71	6.97	37.44 (2.43)	2.01 (.05)	1.24 (.11)	1.33 (.06)

S09	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	58.50 (4.57)	1.94	11.28	26.99 (2.52)	1.93 (.08)	1.24 (.10)	1.20 (.04)
C2	67.64 (4.64)	1.95	13.15	29.09 (2.50)	1.98 (.08)	1.16 (.09)	1.22 (.03)
C3	44.98 (5.97)	1.64	7.25	30.50 (2.81)	1.95 (.09)	1.14 (.13)	1.22 (.03)

S10	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	34.68 (4.95)	2.12	7.22	34.88 (1.05)	2.46 (.04)	No IP	1.32 (.02)
C2	32.59 (3.77)	2.32	7.46	33.07 (1.05)	2.40 (.04)	No IP	1.33 (.03)
C3	24.98 (5.34)	1.72	4.09	34.60 (1.39)	2.40 (.04)	No IP	1.33 (.03)

S11	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	No data	No data	No data	34.34 (1.58)	2.07 (.05)	1.38 (.12)	1.46 (.04)
C2	38.42 (2.83)	2.72	10.41	31.55 (1.42)	2.20 (.05)	1.47 (.12)	1.45 (.03)
C3	27.95 (3.92)	1.89	5.18	32.28 (1.35)	2.18 (.05)	1.41 (.11)	1.45 (.03)

S12	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	35.46 (5.60)	2.15	7.44	41.45 (2.93)	1.94 (.05)	No IP	1.43 (.03)
C2	35.67 (4.07)	2.28	8.03	36.27 (2.84)	2.09 (.05)	No IP	1.42 (.04)
C3	19.02 (3.36)	1.96	3.62	38.49 (2.65)	2.07 (.04)	No IP	1.42 (.03)

S13							
	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	26.20 (2.22)	1.67	4.34	48.09 (3.31)	1.73 (.03)	1.25 (.08)	1.43 (.03)
C2	28.53 (3.62)	1.81	5.11	52.64 (4.25)	1.72 (.05)	1.23 (.09)	1.44 (.03)
C3	21.26 (5.13)	1.91	3.82	49.14 (3.48)	1.81 (.06)	1.36 (.07)	1.47 (.03)

S14							
	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	51.44 (5.31)	1.75	8.88	34.90 (3.61)	2.09 (.06)	1.17 (.10)	1.30 (.05)
C2	58.65 (8.09)	1.65	9.47	35.77 (3.01)	2.15 (.06)	No IP	1.32 (.03)
C3	52.10 (8.48)	1.44	6.52	33.02 (2.89)	2.11 (.05)	1.19 (.10)	1.29 (.04)

S15							
	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	37.54 (5.85)	1.82	6.69	32.87 (2.82)	1.80 (.05)	1.14 (.11)	1.33 (.05)
C2	30.41 (4.42)	1.66	4.97	34.24 (2.92)	1.77 (.05)	1.13 (.10)	1.33 (.03)
C3	19.46 (6.17)	1.56	2.72	32.68 (2.50)	1.79 (.05)	1.16 (.10)	1.31 (.04)

S16							
	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	40.18 (4.72)	2.45	9.70	26.62 (2.75)	2.53 (.15)	No IP	1.37 (.05)
C2	35.96 (5.68)	2.04	7.17	25.08 (2.04)	2.45 (.10)	No IP	1.41 (.08)
C3	35.91 (5.45)	2.41	8.44	23.62 (2.06)	2.55 (.11)	No IP	1.37 (.06)

S17							
	VBM	BBS	ACC	VSTIFF	APGRF	IPGRF	SF
C1	48.14 (6.36)	1.99	9.44	29.63 (1.61)	2.48 (.10)	1.77 (.14)	1.35 (.07)
C2	44.57 (6.35)	2.48	10.80	30.31 (1.62)	2.53 (.08)	1.72 (.14)	1.39 (.06)
C3	35.12 (4.67)	2.23	7.59	29.35 (1.85)	2.55 (.09)	1.79 (.14)	1.37 (.09)