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KINEMATIC AND KINETIC EVALUATION OF HIGH SPEED BACKWARD RUNNING

by

ALAN WAYNE ARATA

A DISSERTATION

Presented to the Department of Exercise and Movement Science
and the Graduate School of the University of Oregon
in partial fulfillment of the requirements
for the degree of
Doctor of Philosophy

June 1999

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"Kinematic and Kinetic Evaluation of High Speed Backward Running," a dissertation prepared by Alan W. Arata in partial fulfillment of the requirements for the Doctor of Philosophy degree in the Department of Exercise and Movement Science. This dissertation has been approved and accepted by:

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The purpose of the study was to investigate the kinematic and kinetic parameters associated with high-speed backward running (BR). Thirty male subjects from two groups (15 Elite who used BR during athletic competition and 15 Athletic habitual runners) performed running trials for each of the following conditions: maximum velocity BR (BRmax), 80% of maximum BR, 60% of maximum BR, maximum velocity forward running and FR (FRmax) at a velocity equal to BRmax. Sagittal view high speed video (200 Hz) and force platform data (1000 Hz) were obtained and the following parameters were evaluated: stride length, stride frequency, intrinsic support length, stance time, trunk angle, hip, knee and ankle ranges of motion, hip, knee and ankle loading rate, resultant active peak, time to resultant active peak, initial anterior-posterior (A-P) peak, and final A-P braking force. Separate repeated measures ANOVAs were conducted to compare a) BR velocity conditions, b) equal efforts for BR and FR, and c) equal velocities for BR and FR.

Results indicated that as BR velocity increased, 63% of the parameter values increased linearly. Intrinsic support length, ankle range of motion, knee angular velocity and impact peak time (as a percentage of stance time) did not change. Stance time, vertical oscillations, and resultant active peak time (as a percentage of stance time) decreased linearly. Seventy percent of the FRmax parameter values were greater than BRmax values, with the following exceptions: stride frequency, stance time, hip angular velocity at toe-off and resultant active peak time. In addition, trunk angle at ground contact and resultant active peak time (as a percentage of stance time) showed no significant differences. Equal velocity BR and FR were fairly evenly split between greater and lesser value parameters, with 21% of the comparisons indicating no significant differences. For all conditions, the Elite group averaged an 87% greater velocity than the Athletic group. Independent of velocity, the following parameters could explain the greater Elite group velocities: stride length, intrinsic support length, time to impact peak, loading rate, resultant active peak, time to resultant active peak and initial A-P peak.

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DEDICATION

I would like to dedicate this dissertation and degree to my sons Bryce and Ryan Arata -- you both have the potential to be so much more than I.

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CHAPTER I

INTRODUCTION

With the advent of competition, humans have been looking for ways to enhance performance and increase chances of victory. Forward running (FR) has benefited from a great deal of investigation because, as a form of locomotion, it is the basis for a number of competitive sports as well as health and fitness activities. With topics covering cardiovascular fitness to injury mechanisms to proper mechanics for fast running, an enormous amount of time has been poured into FR research. Backward running (BR), on the other hand, has not received this kind of attention. It has recently been investigated on motor control/motor learning and rehabilitation bases, but no investigations have been conducted with sports performance in mind. Only Bates, Morrison and Hamill (1986) have mentioned the importance of BR in sport, noting that it was done in quick bursts on athletic fields or courts. It is curious that BR has seen so little research, as it plays an important role in a number of highly competitive team sports, including football, basketball, soccer, lacrosse and other team competitions played in similar settings.

In football for example, a defensive back employing BR can keep both the receiver and the quarterback in his field of vision. Once the defensive back turns to run forward, he loses sight of one if not both of these players, placing him at a disadvantage since both the quarterback and the receiver know where the ball is supposed to go. Sports like soccer, basketball, and lacrosse, and other sports where a ball travels from one end of a field or court to another and in which running is the mode of transportation are all enhanced by BR. Superior speed at BR is an advantage for the above mentioned football defensive back or a player in any of these sports, because with greater speed they can keep their eyes on the ball, the player with the ball, and or other surrounding players longer, allowing them to better defend attacks.

Since high level performance in the sports listed above is lucrative business, one might think the BR aspect of sport would be thoroughly investigated so that athletes could reach their optimal BR performance. This has been done for FR in sport. But as stated above, there has been no BR research directed towards sports improvement. The topics of the limited BR research that do exist are, kinematics of BR movement at moderate velocities, and muscle force and joint moments. There has been no research aimed at improving BR performance in highly skilled athletes who use BR.

The reason for this lack of BR research may be that coaches do not separate backward running as a skill that is different from forward running.

Jim Radcliff, University of Oregon Strength Coach and former National College Athletic Association (NCAA) defensive back says, "It's (BR) not something that everybody can just automatically be good at." He says that BR is important for three reasons: (a) the ability to move while looking down the field, (b) recovery/rehabilitation, and (c) movement efficiency and balance.

A question that needs study is whether FR and BR have similar gait characteristics at high speeds (maximum efforts). For example, the characteristic of maximum stride frequency may be limited by several factors, including length of limb, force production of the muscles, the task, the environmental conditions, the morphology of the individual, and a running motor program. In kinematically and kinetically comparing a maximum BR effort to a maximum FR effort, several of these factors can be controlled for and measured, helping to answer this question.

Winter, Pluck, and Yang (1989), in an investigation of the similarities and differences in forward and backward walking, concluded that backward walking was a 95% reversal of forward walking. This was true for joint movement patterns and joint powers. Conversely, Devita and Stribling (1991) in their investigation of lower extremity joint moment and joint muscle power with respect to BR found that BR was not simply a reversal of FR. Their results indicated the muscular structure supporting the ankle and knee reversed roles in FR and BR.

Backward running is a learned skill and one that seems to have its own motor program. The average individual does not spend a lot of time performing BR. This is quite different from FR, which is developed early in life. Lundberg (1979) studied locomotion in children and found that ninety percent could run (forward) at 18 months, though stiffly. Normal individuals have a strong motor program for forward running (FR). Currently, no study has been published recording when children learn the skill of BR.

Studying how a sedentary individual performs BR may have little value. These individuals may never perform BR throughout their lives. Though BR may find some uses as a balance control exercise, athletic individuals performing some activity mainly use it. These activities may be sports or rehabilitation related. Therefore, to better study the parameters of high speed BR, individuals who are highly experienced in BR (elite BR users) should be used as subjects. In choosing a control group for comparison, an athletic population of skilled movers should be used, since athletically unskilled individuals might have difficulty performing BR.

Purpose of the Study

The purpose of the study was to quantify the kinematic and kinetic parameters associated with backward running. High velocity BR parameters were then compared to: (a) BR parameters at submaximal velocities, (b) FR parameters at maximum velocity, and (c) FR parameters at a velocity equal to BR max. In addition, two groups were compared. One group was made up of individuals who used BR during athletic competition while the other group was comprised of individuals who ran as a form of exercise. The kinematic parameters included stride rate and stride frequency, as well as joint angles, and velocities at the hip, knee and ankle. The kinetic parameters included braking and propulsive forces during stance phase.

Need for the Study

Backward locomotion has found application in sports, rehabilitation, and motor control. Beyond this, backward locomotion is used by all ages, from kindergarten soccer players to elderly individuals performing balance control tests. Yet for all its wide range and variety of use, extremely little research on BR has been conducted. This study may provide a baseline for others, especially in determining the characteristics of high speed BR. The results of this study might provide coaches and athletic trainers with practical knowledge of how to improve an athlete's BR speed. Furthermore, the data obtained during submaximal BR can be used in rehabilitation when devising protocols for specific muscle and joint injuries.

Delimitations

The results of this study cannot be extended beyond the limits in which the data were collected:

1. The participants in the study were highly experienced male athletes who used BR in their sports and athletic male college students. The subjects were 18 to 28 years old. The highly experienced BR athletes were currently training for their sport. The athletic male college students were involved in a runningprogram.

2. Kinematic variables were obtained using two-dimensional sagittal view videography. Two cameras were used, each set up to film a three meter section of the runway with 50 cm of overlap.

3. Kinetic data were taken from a single foot-fall on a force platform during the test runs.

4. All data were obtained in one testing session.

5. Submaximal running speeds were based on the subject's maximal BR velocity.

Limitations

The known limitations of this study are noted below:

1. Limitations of the video collection system included but were not limited to: centroid location of the marker, coordinate error if movement occurred out of the plane of the camera lens, marker obstruction by extremities during motion, and possible movement of markers on the skin.

2. The joint centers of rotation during marker placement were estimated.

3. The length of the runway in line with the force plate may not have been long enough for subjects to reach their maximum velocity.

4. The stopping distance between the video collection area and the crash padded wall may have caused subjects to change their footfalls and body positions while still in the video area during FR.

5. It was understood that the results of this study would not solely explain how some individuals perform BR at higher velocity than others.

Assumptions

1. Subjects performed their natural movements, unaltered by laboratory set up and the force platform.

2. The markers placed on the subjects represented their joint centers.

3. The sampling equipment used performed reliably and the sampling rate was sufficient to capture the critical events measured.

4. The experimental design and protocol were sufficient for the investigation.

5. Subjects were running at their maximum effort during the FRmax and BRmax conditions.

6. The synchronization light came on at ground contact and went off at toe-off.

Definitions

The following terms are found throughout this dissertation:

Anterior-posterior Force - The component of the ground reaction force (GRF) exerted in the anterior or posterior direction of the runner (y-component).

Backward Running - BR - Running movement displaying a flight phase in the direction posterior to the body.

Body Weight - (BW) Force produced divided by the individual's body weight. During normal stance, an individual exerts 1 BW of force on the ground.

BR_{60} - Backward running performed at 60% of the subject's maximum velocity.

BR$_{80}$ - Backward running performed at 80% of the subject's maximum velocity.

BRmax - Backward running performed at the subject's maximum velocity.

Elite - Used in conjunction with subjects, meaning an individual who had reached a very high level in his/her respective sport. "Very high level" for this study meant a Division I National College Athletic Association (NCAA) active University athlete.

Flight Phase - The period of time during the running motion when no foot is in contact with the running surface.

Foot-off - The instant in time and position just before the foot leaves the running surface.

Forward Running - FR - Running movement displaying a flight phase in the direction anterior to the body.

FRequal - Forward running performed at the same velocity as the subject's BR maximum velocity.

FRmax - Forward running performed at the subject's maximum velocity.

Ground Contact - The instant in time and position when the foot initially makes contact with the running surface.

Ground Reaction Force - GRF - The supporting force from the ground in reaction to the force the runner exerts on the ground.

Impact Phase - The initial portion of the support phase when the foot impacts the running surface.

Intrinsic Support Length - The horizontal distance from the body's center of gravity to the toe at ground contact and toe-off.

Joint Angle - The angle defined by two adjacent segments or links.

Leg Length - Length of the shank and thigh segments combined, measured via video data.

Loading Rate - The change in force over a change in time. The loading rate for this study was calculated during the impact phase (first 20% of the stance time) with units of $BW \cdot s^{-1}$.

Medial-lateral Force - The component of the GRF exerted in the horizontal plane, perpendicular to the direction of movement (x-component).

Phase - A portion of a stride with a distinct beginning and ending.

Resultant Active Peak - The resultant active peak was recorded as the greatest resultant vertical and A-P force between 20-100% of stance time.

Resultant Impact Peak - The resultant impact peak was recorded as the highest resultant vertical and A-P force within the first 20% of stance time.

Running Velocity - The average horizontal speed of the runner in the sagittal plane.

Stride - The movement from ground contact of a specific foot to the subsequent ground contact of the same foot.

Stride Frequency - The number of strides taken in a specific time interval, usually one minute.

Stride Length - The horizontal distance covered during a complete stride.

Successful Trial - A trial in which the subject landed with his entire foot on the force platform in a normal stride for the velocity required and maintained that velocity through the timing light system.

Stance Time - The portion of the stride during which a foot is in contact with the running surface.

Swing Phase - The portion of the stride during which a foot is not in contact with the running surface -- from toe-off the running surface until foot on the running surface.

Target Range - Velocity plus or minus 5% of the target velocity.

Target Velocity - Velocity based on a percentage of the maximum BR velocity (100%, 80% or 60%).

Trunk Stability - The absolute value of the trunk angle at ground contact minus the trunk angle at toe-off.

Vertical Force - The component of the GRF exerted in the direction perpendicular to the running surface (normal, or directly upward from the ground) (z-component).

Vertical Oscillation - The change in vertical position of the hip marker over one stride.

CHAPTER II

REVIEW OF LITERATURE

For early man, running was a means to aid survival. Faster running meant a closer distance to prey or a further distance from enemies. Then came the advent of sports. In the ancient Olympics, running was part of the Pentathlon, a five sport event for which the winner was crowned the "greatest athlete." The running race in the ancient Pentathlon was approximately 200 meters. Today, fast running is not key to human survival, but humans of all ages compete in various sports where the ability to run swiftly is a primary component. The competitive nature of the human race from ancient times until today makes us continually seek methods to run faster.

The ability to run backward quickly has never been necessary for human survival. Today BR is mainly used in sporting events. Soccer, whose players use BR when playing defense, was invented in the Middle Ages. Most of the sports in which players use BR, however, have only been around for the past 125 years. Thus, any genetic traits which may make an individual excel at BR would not have made their way into the population as they would have for FR.

The discussion of anatomical limitations and relevant literature presented in this chapter will help to shed light on important aspects of fast BR. Since there have been no studies investigating maximum velocity BR, this review will begin with biomechanical factors that create velocity during running, backwards or forwards, followed by an examination of the kinematics and kinetics of sprint FR. Then the backward locomotion studies that have been published will be reviewed, followed by a summary.

Anatomical Constraints of FR and BR

To comprehend the differences between BR and FR, one must understand the anatomical constraints of the hip, knee and ankle joints and how these constraints affect backward and forward running.

The hip joint is ultimately constrained in flexion by the physical contact of the quadriceps with the chest or musculo-tendonous units spanning the hip and the knee. In extension, the hip is constrained by the anterior musculo-tendonous units spanning the hip joint. There is no movement in either FR or BR that requires maximum flexion of the hip joint. However, both FR and BR can require full extension at the hip. In FR, the hip can reach full extension at or just after toe-off. In BR, the hip can reach full extension just prior to ground contact. Thus, the hip joint may constrain BR velocity by not allowing sufficient extension at ground contact. In FR, the hip joint may constrain velocity by not allowing sufficient extension at toe-off. In both directions, effective hip extension can be gained by increased trunk lean, which decreases hip angle.

The knee is constrained in flexion by the physical contact of the hamstrings muscle groups with the gastrocnemius. Extension of the knee is constrained by ligaments, posterior muscles and bone. Maximum velocity of forward running may be constrained slightly in knee flexion, however, it is unlikely that increased knee extension would increase running velocity. The knee does not constrain BR in flexion, but may in extension at or near toe-off. If the knee were able to hyperextend without injury, BR ground contact time could increase, which could potentially increase propulsive force. BR requires muscular work as the knee reaches full extension at toe-off. Knee joint proprioceptors sense joint extension and send neurological signals to activate antagonistic muscles. This action avoids damage to the knee joint structure, but the antagonistic muscular force is counterproductive to BR velocity.

The ankle is constrained in flexion and extension by bone, ligaments and musculo-tendonous units. It is unlikely that normal ankle ROM constrains FR (reduced plantarflexion may limit the ability to produce force). Like the knee, the ankle is not constructed for backward locomotion. From the standing position, ankle plantarflexion produces forward movement. BR is thus constrained during the stance phase. In addition, as the runner moves backward, the ankle angle increases as opposed to decreasing as in FR, lessening the amount of plantar flexion available and thus limiting propulsive potential.

Forward and backward running differ in their utilization of major thigh muscles during running propulsive and swing phases with respect to the hip and knee joints. During the BR propulsive phase, the rectus femoris is involved in hip flexion and the entire quadriceps group (rectus femoris, vastus lateralis, medialis, and intermedius) extends the knee. During the FR propulsive phase, the quadriceps group is responsible for knee extension only. Additionally, hip extension is aided by the hamstring group (biceps femoris, semitendinosus, and semimembranosus). FR's greater muscle utilization over BR during the propulsive phase gives FR the potential for more force production. During swing phase, BR utilizes the same muscles as FR does during its propulsion phase. Conversely, FR swing phase muscular utilization is similar to the BR propulsion phase. This means that more muscles are at work in BR than in FR during the non-propulsion or resting phase. Thus, FR employs a greater muscular potential during propulsion and is muscularly more efficient during swing phase than is BR.

Running Velocity

In running, backward or forward, velocity is equal to stride length multiplied by stride frequency. Therefore, to increase running velocity, one must increase either stride length or stride frequency without proportionally decreasing the other, or increase both.

Slocum and James (1968) investigated the length of the running stride and determined that it depended on three variables: (a) the relative leg length of an individual with respect to the remainder of the body, (b) the force that was exerted after the mid-stance portion of the support phase, and (c) possible deceleration caused by over extension of the foot prior to ground impact.

Breaking down Slocum and James' three points can give investigators and practitioners insight into improving sprint performance. Referring to the first variable, an individual's leg length cannot be changed after the individual has reached adulthood. Even while individuals are growing, leg length is not a factor that can be changed. Therefore, improved performance must be associated with the other two variables. Improvement in the second variable, force exerted after mid-stance, is possible. The force exerted after mid-stance is a function of the individual's conditioning at the specific motion. Individuals attempt to improve this portion of their velocity through training.

Finally, Slocum and James talk about increased stride length and possible deceleration. An increase in stride length, which might be categorized as overstriding, causes greater braking forces due to over extension of the foot. Stride length increases without associated decreases in stride frequency do increase running velocity. Therefore, an increase in stride length can be both beneficial and detrimental. In order for a stride length increase to be beneficial, proper technique to prevent overstriding and excess deceleration must be employed.

There have been a number of studies (Deshon & Nelson, 1964; Luhtanen & Komi, 1978; Mero & Komi 1986; Nelson, Dillman, Lagasse, & Bickett, 1972; Sinning & Forsyth, 1970) that have concluded that as running velocity increases, stride frequency and stride length both increase. Mero, Komi, and Gregor (1992) noted that increasing trends in both stride frequency and stride length are linear up until around 7 $m \cdot s^{-1}$. After that point, there are small increases in stride length, and further increase in overall velocity is predominately a factor of increasing stride frequency. Thus, these researchers have concluded that stride frequency contributes more to maximum sprint velocity than does stride length. Mann and Herman (1985) noted that stride frequency can be as high as 300 strides $\cdot$ min^{-1} with a stride length as high as 2.6 m. Dick (1989) observed both Ben Johnson and Carl Lewis running at 12.05 $m \cdot s^{-1}$ between the 50 and 60 meter mark of the 1988 Olympic 100 meter final. If these two athletes had stride lengths of 2.6 m, that would put them at 278 strides•min^{-1}.

These studies raise interesting questions about what might be expected during BR and what similarities there may be in FR and BR performed by the same individual. As BR velocity increases, do stride frequency and length both increase linearly until about 60% of the individuals maximum velocity? Are increases in stride frequency the predominant influence in increases in BR velocity? Also, is stride frequency for FR a good predictor of stride frequency for BR. Do individuals have a maximum stride frequency that they can produce regardless of stride length, and if so, does stride frequency for maximum velocity FR equal stride frequency for maximum velocity BR?

Biomechanics of Forward Sprint Running

One of the first individuals to investigate the kinematic aspects of running was Amar in 1920 (Dillman, 1975). He concluded some of the biomechanical aspects affecting sprint running were reaction time, technique, electromyographic activity, force production, neural factors and muscle structure, and that some external variables that affected running velocity were shoes and running surface. All of these factors and more can be listed in both internal and external categories today. Some, such as reaction time, which means time from the starter's gun until movement begins, will not be investigated in this study with respect to BR. All these factors play a role in FR and BR maximum velocity, but this study will focus mainly on technique, force production, and to a lesser extent, neural factors.

Early FR studies on sprinting have shown the velocity-time curve can be broken down into three phases: acceleration, constant velocity and deceleration (Volkov & Lapin, 1979). The constant velocity phase of sprinting is where the speed of the individual is at its maximum. Variables related to technique during maximum velocity running would include foot-plant, time during stance phase, and braking and propulsion forces during stance phase. Technique would also include range of motion of the hip, knee and ankle, as well as force production and timing of that force from the involved muscles.

Kunz and Kaufmann (1981) conducted one study that had subjects grouped in a similar manner to the present. They compared the kinematic sprinting parameters of world class decathletes to those of world class 100 meter sprinters. Their results indicated the world class sprinters differed from the decathletes by having: (a) both greater stride length and stride frequency, (b) a greater angle between the shank and the ground at ground contact, (c) a greater average thigh angular acceleration, and (d) a larger trunk-thigh angle at foot-off.

Mann and Hagy (1980) examined the FR kinematic differences of individuals running at 5.3 $m \cdot s^{-1}$ and the same individuals sprinting at 7.2 $m \cdot s^{-1}$. They noticed when sprinting, individuals had a lower center of gravity than when running, which they attributed to increased knee and hip flexion during the stance phase. Generally, as running speed increased, there was an increase in hip flexion. Overall, the subjects exhibited 10 - 15% greater hip flexion when sprinting than when running. It is unknown whether this same trend will be seen during BR. Some backward locomotion study results that will be discussed later infer the opposite may be true for backward locomotion.

With respect to kinetic forces, Luhtanen and Komi (1978) reported that contact time during the support phase decreased as running velocity increased. They divided the stance phase into braking and propulsion phases. During the braking phase, the body's center of gravity moved downward, while during the propulsion phase, the body's center of gravity moved upward. Not surprisingly, Cavanagh and LaFortune, (1980) found that during the braking phase, the body's velocity decreased, while during the acceleration phase, it increased. Overall, the acceleration phase showed faster velocity at foot-off than at foot down, which could be attributed to air resistance during the flight phase.

As running velocity increases, both vertical and anterior-posterior force production increase (Mero & Komi, 1986). No medial-lateral data for sprint running could be found, though small increases in medial-lateral forces were seen with an increase in velocity at slow running speeds (Cavanagh & LaFortune, 1980).

Biomechanics of Backward Locomotion

Backward locomotion studies have only been conducted for the past 15 or so years. Most of the backward walking studies have been from a motor control perspective, attempting to determine what gait parameters and motor programs were used. BR studies have been conducted primarily from an aid to injury rehabilitation viewpoint.

The first published BR study came from Bates, Morrison, and Hamill (1986) who compared joint angles during BR and FR in 9 female runners at one backward and two forward running speeds. They compared equivalent speeds for BR and FR (2.7 $m \cdot s^{-1}$ FR vs. BR) and equivalent efforts (3.0 $m \cdot s^{-1}$ FR vs. 2.7 $m \cdot s^{-1}$ BR). The results are summarized in Table 1.

Table 1. Mean Knee Angles Measured at Takeoff and Landing of 9 Female Runners. Bates, B. T., Morrison, E., & Hamill, J. (1986)

Position	2.7 FR	3.0 FR	2.7 BR
Landing	167°	165°	140°
Takeoff	168°	169°	178°

The study results indicated BR, when compared to FR, had lesser ranges of motion at both the knee and hip with respect to stance phase. This study did not measure stride rate. However, one can surmise that BR stride rate is greater than FR stride rate given decreased range of motion (which should equate to decreased stance phase time) of the 2.7 $m \cdot s^{-1}$ BR compared to the $2 \cdot 7 m \cdot s^{-1}$ FR.

Vilensky, Gankiewicz, and Gehlsen (1987) conducted a study that employed incremental increases in backward walking velocity. Their results showed a decrease in the subject's maximum knee angle as velocity increased. This is different than the trend seen in forward running where knee angles increased as velocity increased (Mero & Komi, 1986).

Another backward walking study was conducted by Winter, Pluck, and Yang in 1989. They found that backward walking was a 95% reversal of forward walking when both were done at moderate walking speeds. This was true for joint movement patterns and joint power.

Conversely, Devita and Stribling (1991), in their investigation of lower extremity joint moment and joint muscle power with respect to BR, found that BR was not simply a reversal of FR. Their study used five volunteer male participants, one with experience using BR. Measurements were taken from digitized video and combined with force platform analysis including ground reaction forces. Their results indicated the muscular structure supporting the ankle and knee reversed roles in FR and BR -- During BR, the knee provided the primary power while the ankle plantarflexors absorbed shock.

Threlkeld, Horn, Wojtowicz, Rooney, and Shapiro (1989) investigated BR ground impact forces. They had an experimental group practice BR for 8 weeks as part of a daily running routine, while a control group only practiced FR. Their study investigated BR at 3.5 $m \cdot s^{-1}$, attempting to emulate the FR training speed of good to elite distance runners. They concluded there were significant increases in muscular strength of the knee extensors within the BR group as a result of BR training. They also noted that the BR stance time was 10% shorter than FR stance time. There was a 6% lesser maximum vertical force and a 30% lesser impulse force in BR compared to FR (at 3.5 $m \cdot s$). The investigators hypothesized that the decrease in the BR group impact forces was seen because the toe landed first in BR and allowed more shock absorption than the heel that struck first in FR.

Flynn and Soutas-Little (1993) investigated muscle power and action during FR and BR, analyzing the sagittal plane of the right knee. The study compared EMG and kinetic parameters during the stance phases of FR and BR using 6 active male subjects. Their results indicated that during the initial stance phase of running, more work was required for FR than BR. This was found true especially for eccentric muscle contractions where four times more work was required for FR than BR.

Flynn, Connery, Smutok, Zeballos, and Weisman (1994), when studying oxygen consumption during forward and backward walking and running, found 40% of their participants were not able to complete the BR test at a relatively slow (compared to FR) speed over a 6 minute time. The researcher's qualitatively observed the subjects and concluded that high fatigue and or loss of coordination was the cause. The study also noted that the participants who dropped out of BR were not the slowest at FR.

All the above studies can be combined for some general conclusions. Firstly, BR and FR are not just reversals of the same movement. Secondly, an individual who possesses skill and speed in FR may not possess them in BR. Thirdly, high speed BR has not been investigated.

Summary

An attempt has been made to review the kinematic and kinetic sprint literature. Stride length and frequency have been well documented, as well as other aspects of sprint running. Still, there are literally millions of individuals who practice to improve their running velocity with little idea of the factors that influence running speed. With respect to forward running, sprinting has been extensively researched, and answers on how to improve performance have been determined and implemented. The same cannot be said for BR with respect to sprinting. Any BR sprinting judgments would be guesses from FR or interpolations from BR rehabilitation research. This dissertation aimed to answer many BR sprinting questions, as well as lay the ground work for future BR studies.

CHAPTERIII

PROCEDURES

The purpose of the study was to quantify the kinematic and kinetic parameters associated with backward running. High velocity BR parameters were then compared to: (a) BR parameters at submaximal velocities, (b) FR parameters at maximum velocity, and (c) FR parameters at a velocity equal to BR max. The kinematic parameters included items such as stride rate and stride frequency, as well as joint angles, and velocities at the hip, knee and ankle. The kinetic parameters included ground reaction forces (GRF), braking forces, and propulsive forces as well as the time intervals associated with these forces.

Subjects

Thirty male volunteers served as subjects for the study and were selected to be in either an Elite or Athletic group. The Elite group was comprised of 15 subjects who were members of a Division I university athletic team for which they needed to perform high velocity BR as a part of their competition (average age 21±1.37, height 184±7 cm, weight 87±8.66). The

Athletic group was comprised of 15 healthy college students involved in a running fitness program (average age 22±2.66, height 181.6±6.66 cm, weight 77±8.52). The two groups of subjects ranged in age from 18 to 28 years and all were free of any musculoskeletal injures at the time of testing. At the beginning of the testing session, each subject completed an Informed Consent Form (Appendix A) approved by the Office of Human Subjects Compliance at the University of Oregon, and a BR questionnaire (Appendix B).

Instrumentation

Kinematic, kinetic and velocity data were obtained for each subject during five different running conditions. Kinematic data were collected using a Motion Analysis Corporation video system. Two NEC high-speed cameras with Augenieux Zoom Type 10 X 120A lenses were set up to view and record sagittal plane motion at 200Hz. The cameras were set eight meters from the force platform and perpendicular to the path of motion. The cameras were set up beside each other with a horizontal field of view approximately 3.5 meters. There was approximately 0.5 meters of overlap of the viewing fields, giving a total horizontal filming distance of 6.5 meters. Each camera was leveled using a bubble level and set to a height of between 1.4 and 1.6 meters.

Five light markers were placed on selected anatomical landmarks to help identify joint centers of rotation. These markers were placed and numbered as follows: (1) neck on the mastoid process, (2) greater trochanter, (3) lateral epicondyle of the knee, (4) lateral malleolus, (5) lateral head of the fifth metatarsal. Marker placement is shown in Figure 1.

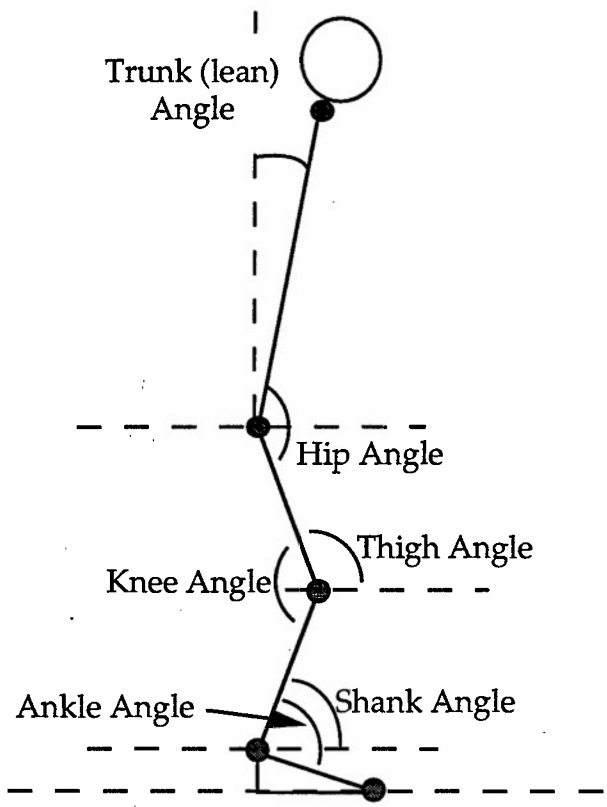

Figure 1. Placement of Light Markers and Joint/Segment Angles to be Measured.

The light markers were developed by the investigator specifically for this project. Each light was a Radio Shack model number 1166, 8.72 volt flashlight bulb. The light bulbs were embedded in a half round Styrofoam 1.5 inch diameter ball with a plastic backing, made to contour to a specific landmark on the body. The bulbs were connected in series and powered by four 9 volt alkaline batteries. The batteries were held in an elastic belt the each subject wore around his waist. The lights were turned on and off with a push-button switch in the middle of the belt. The light markers can be seen in Figure 2.

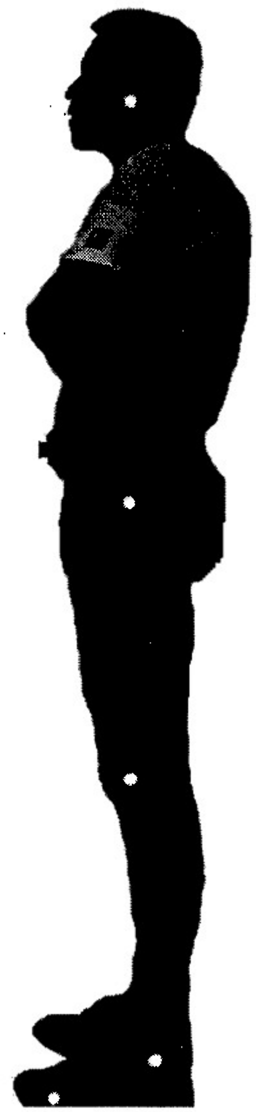

Figure 2. Light Set Developed for Video Capture with Two Parallel Cameras.

The marker positions were processed into planar coordinates via the Motion Analysis VP320 video-processor interfaced to a WINTEL 80486 computer system running ExpertVision™ software (Version 3.1, Motion Analysis Corporation). Video records were obtained for between 1.5 and 2.0 seconds (300-400 frames), depending on the velocity of the subject and trial, to include 30 frames of data prior to and following the complete stride.

A light reference frame was used to scale the kinematic data. The reference frame consisted of three of the same lights used on the light belts powered by two 9 volt batteries. The lights were placed one meter apart, both horizontally and vertically. All reference data was collected prior to subject data collection. An example of the reference frame is given in Figure 3.

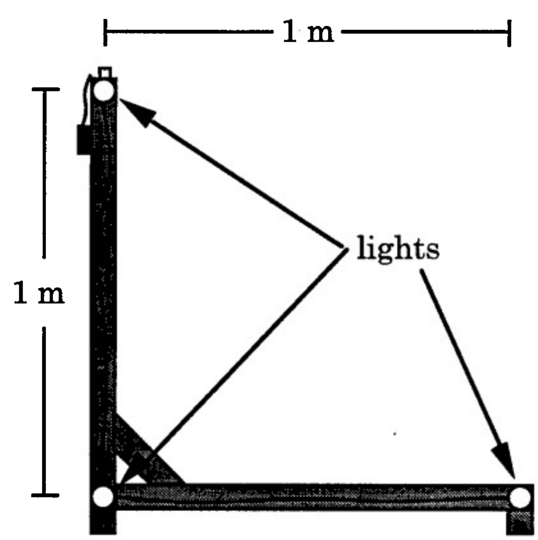

Figure 3. Light Reference Frame.

Ground reaction force data were obtained using an AMTI force platform (Advanced Medical Technologies, Inc. Model OR6-5-1). All data were collected at 1000 Hz on separate analog channels using the Ariel Performance Analysis System (APAS). An AMTI signal amplifier (Model SGA6-3) was used to amplify the analog signal prior to inputting it to the APAS. Forces were separated into vertical (Fz), anterior-posterior (Fy) and medial-lateral (Fx) components. In addition, the first channel (Fz) was used to synchronize the forceplate and video system data using a foot contact activated LCD light. The force platform was mounted flush with the hardwood floor of the laboratory at approximately the 20 meter mark of a 30 meter runway. The force platform was mounted on a stainless steel plate covering a concrete pier.

The total kinetic sampling period was 0.5 seconds with a pre-trigger set at 10%. This resulted in sampling 50 data points prior to and 450 data points following ground contact. The pre-trigger was used to insure that the baseline force platform data were consistent over the testing period and that no data were lost prior to ground contact.

To time the subjects, Lafayette Performance timing lights (Lafayette Performance Pack, Model 63520) were placed in three locations. The first light was located in advance the force platform, the second and the third were placed 2.5 and 5.0 meters beyond the first, respectively. The Lafayette system had a sampling rate of 0.001 seconds. A pictorial representation of the equipment layout is given in Figure 4.

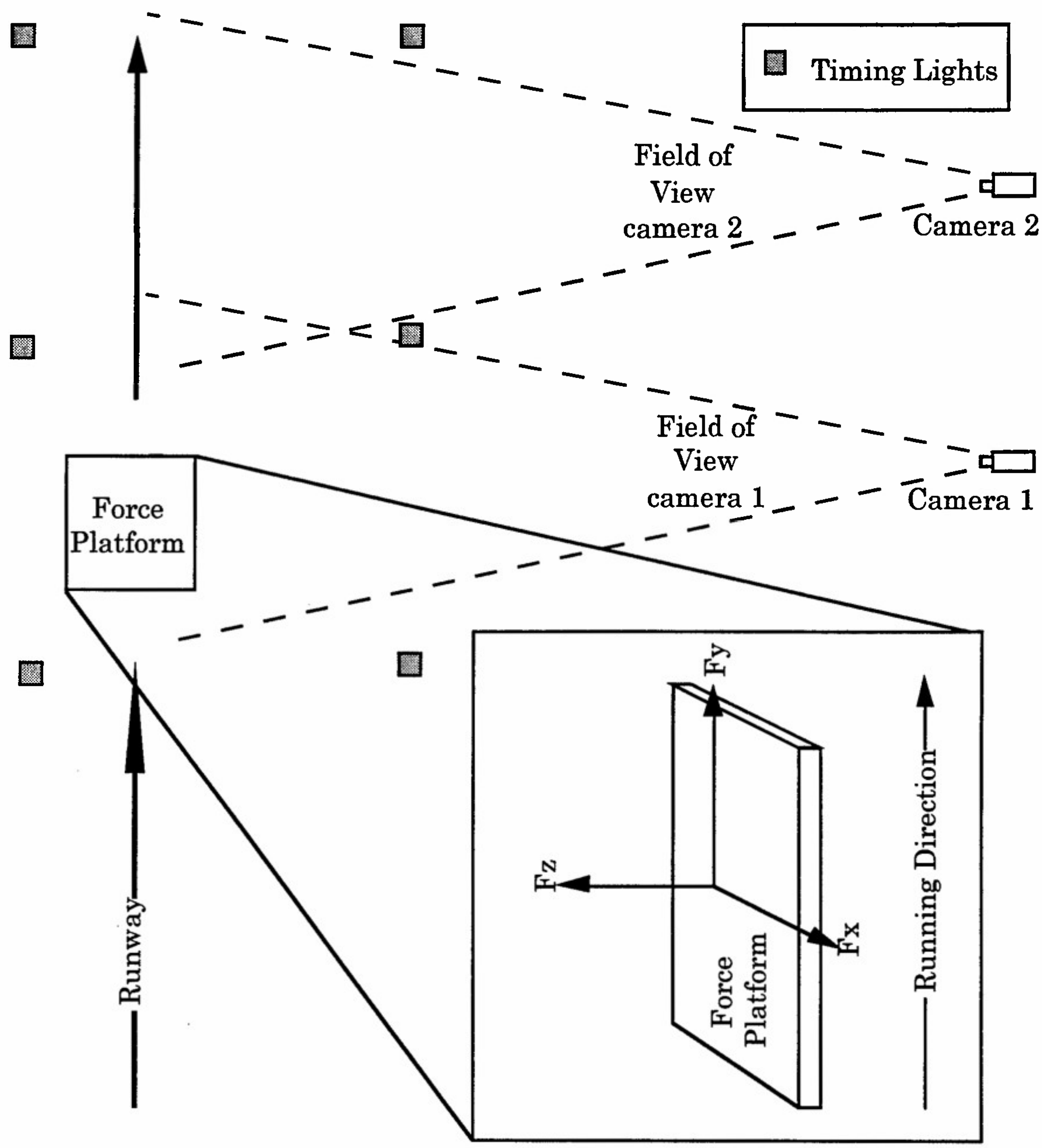

Figure 4. Equipment Set-up in the University of Oregon Biomechanics Laboratory.

Experimental Protocol

Each subject was tested on a single day in the Biomechanics Laboratory at the University of Oregon. The test session lasted between 1 and 2 hours. Subjects were asked to wear a dark shirt and running or lycra shorts for testing. Upon arriving at the laboratory, subject was given an overview of the testing procedure and the opportunity to ask questions before completing an Informed Consent approved by the University of Oregon Human Subjects Review Board (Appendix A). Each subject was weighed on a scale and on the force platform and measurements were taken for overall height. Each subject was give adequate practice time to get comfortable with backward running and become familiar with the testing environment. To help the subject run straight down the runway, a tape line was placed on one side of the force platform. In addition, a full length mirror was situated so that the subject could view himself throughout a trial. After the subject completed a few full speed practice runs, a starting position was estimated so that the subjects left foot would contact the force platform during the actual trial. The subject was then fitted with the light belt, with the light markers placed on the five previously described locations on the left side of the body. Double-sided carpet tape was placed on the plastic backing of each marker and affixed to the specific anatomical location on the subject. Additionally, athletic tape was used for the toe marker and combinations of pre-wrap and athletic tape were used for the knee marker to ensure fixed marker placement throughout the testing session. Once the markers were affixed, the subject stood over the force platform with his left side facing the camera. The lights were illuminated and video data obtained for a natural standing position.

A trial consisted of the subject running through the camera viewing area and activating the force platform with the correct foot while triggering the timing lights. Prior to each trial, the investigator armed and prepared the force platform, the timing lights and the Motion Analysis video system for data collection. After each successful trial, the subject's time was recorded, video data and force platform data were saved and the systems were reset.

Each subject was asked to perform three successful trials at their maximum BR velocity. A successful trial was one in which the subject landed naturally on the force platform with the proper foot and maintained their running velocity through the video area. After each attempt, the subject was given a rest period of at least one minute but, longer if requested. Each subject was given a liter of bottled water from which to drink during the rest period.

After the first three successful BRmax trials, the subject's fastest velocity was determined (taking into account all the trials, including unsuccessful attempts). The subject was then asked to perform three BR trials at both 80% and 60% of their maximum velocity. Each trial had to be within a target range and meet the previously mentioned successful trial requirements. Target range was defined as ±5 percent of target velocity. An example of how target range was determined is shown in Table 2.

Table 2. Determination of Target Speed

Subject's Max BR velocity	6.0 m/s		
5% of 6.0 = .3 m/s			
% of Running Velocity	Low range ($m \cdot s^{-1}$)	Actual value ($m \cdot s^{-1}$)	High range ($m \cdot s^{-1}$)
80 % of BR max	4.56	4.80	5.04
60 % of BR max	3.42	3.60	3.78
FR equal	5.70	6.00	6.30

The timing lights provided only a close approximation of the subjects' velocities. The actual velocities were determined from the kinematic data. This was done by dividing the horizontal distance the hip marker traveled over one stride by the time it took the subject to complete the stride.

After the subject completed the BR trials, the markers were removed and the backing was replaced with new double-sided carpet tape. The markers were then placed on the subject's right side in the previously mentioned five locations and secured with pre-wrap and athletic tape at the toe and knee. Once the markers were affixed, the subject stood over the force platform with his right side facing the camera. The lights were turned on and video data were again acquired of his natural standing position. Following this procedure, the subject received another preparation period to practice FR across the force platform. Once the subject expressed comfort, he performed three successful maximum FR velocity trials. Following these trials, each subject performed three FR trials at his average maximum BR trial velocity (within the target range) (FRequal).

Data Preparation Process

ExpertVision™ software, version 3.1 was used to digitize the video data. This program provided x and y data for each of the markers and for the force platform synchronization light. University of Oregon Biomechanics Laboratory software (Quick Basic) was used to generate continuous paths and delete any unwanted paths. All data were smoothed using a fourth-order low pass Butterworth filter with a selective cut-off algorithm put forward by Jackson (1979). The cut-off frequencies were between 5 and 15 Hz. The Laboratory software output the data in the format shown in Table 3.

Once the marker paths were smoothed and continuous, data were placed into an investigator developed C++ program (Combine.cpp, Appendix D) which combined the data from the two cameras, determined the initial ground contact, the initial foot-off (toe-off) and ipsilateral ground contact. It then restructured the data so that the position coordinates of the same frame number would be next to each other in the order of neck, hip, knee, ankle and toe. The new data file was titled with subject number, condition number, and trial number, followed by .KN3 (i.e. S1C1T1.KN3). Ground contact data (initial ground contact, initial foot-off and ipsilateral ground contact) were placed in the first three columns of the first row, followed by the marker coordinates. Marker coordinate data beginning two frames prior to initial ground contact plus the next 200 frames (1 second) of video data were placed in the restructured data file. An example is given in Table 4.

Table 3. Example Output from Path Editing Program

Marker #	Frame #	X coordinate	Y coordinate
1	1	6.040	222.196
1	2	7.415	222.258
1	3	9.062	222.351
2	1	12.675	161.149
2	2	15.043	161.114
2	3	17.446	161.080
3	1	5.455	123.677
3	2	7.607	123.283
3	3	10.202	122.867
4	1	19.899	91.980
4	2	24.837	93.213
4	3	30.208	94.558
5	1	35.852	81.814
5	2	40.966	82.803
5	3	46.546	83.880
6	1	0.000	0.000
6	2	12.327	85.243
6	3	12.392	85.243

Table 4. Combined Data from the Two Cameras Including Initial Ground Contact (IGC), Initial Toe-Off (TO) and Ipsilateral Ground Contact (2GC)

IGC	TO	2GC
2	38	124

X neck	Y neck	x hip	y hip	x knee	y knee	x ankle	y ankle	x toe	y toe
6.040	222.196	12.675	161.149	5.456	123.677	19.899	91.980	35.852	81.815
7.416	222.258	15.043	161.114	7.608	123.284	24.838	93.214	40.967	82.804
9.062	222.352	17.446	161.080	10.203	122.868	30.208	94.559	46.546	83.880

Once the data from both cameras were combined and placed into the ".KN3" file, an investigator developed program (Kinematic.cpp, Appendix D) calculated the following parameters: velocity, stride length, stride frequency, trunk angle at ground contact (GC), and toe-off (TO), maximum and minimum hip angles and times of occurrence, maximum and minimum knee angles and times of occurrence, maximum and minimum ankle angles and times of occurrence, hip angles at GC and TO, knee angles at GC and TO, ankle angles at GC and TO, hip angular velocities at GC and TO, knee angular velocities at GC and TO, ankle angular velocities at GC and TO, change in height over one stride, maximum horizontal velocity of the ankle, maximum horizontal swing phase velocity of the ankle, the subject's leg length, and the distance between the ankle and hip at GC and TO (actual and as a percentage of leg length).

The kinetic data were exported from the APAS system and analyzed using an investigator developed program (Kinetic.cpp, Appendix D). The kinetic parameters output included: stance time, F1 (resultant impact peak), time to resultant impact peak, maximum slope to resultant impact peak, F2 (resultant active peak), time to resultant active peak, the initial posterior acceleration force and final anterior braking force.

Parameters for three trials for each condition were averaged to obtain the subject's representative value for that condition. A flowchart representation of data processing is displayed in Figures 5 and 6.

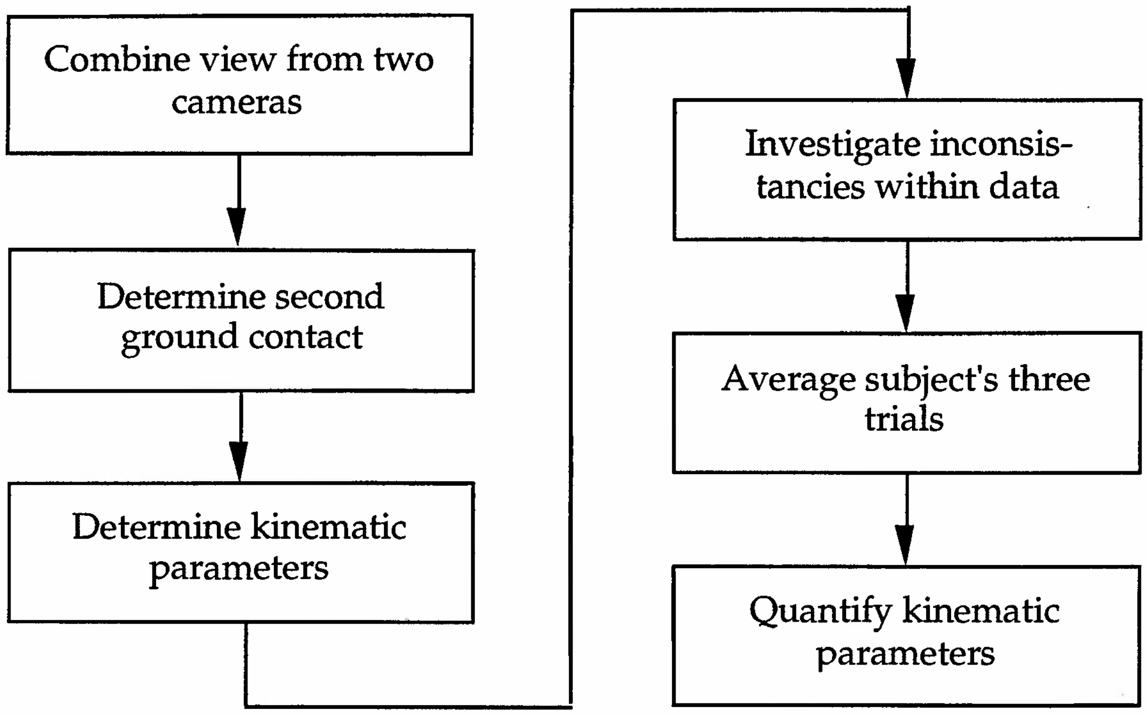

Figure 5. Data Preparation Process for the Kinematic Data.

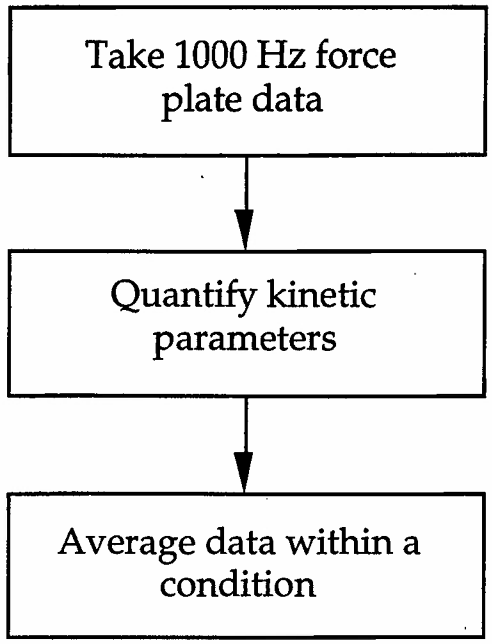

Figure 6. Data Preparation Process for Kinetic Data.

Selecting Data for Analysis

All variables associated with stride (except stance time) were computed using the kinematic data. A stride was defined as the movement from ground contact to the subsequent ground contact of the same foot. Initial ground contact was recorded via a synchronization light controlled by the force platform output. The synchronization light illuminated when the force platform recorded a force value greater than 20 Newtons, indicating the subject's foot was in "contact" with the force platform. Ground contact was associated with the first frame of kinematic data in which the synchronization light appeared. Since there was no second force platform to record the subsequent ground contact, it was identified as the frame when the "y" coordinate of the toe marker recorded its maximum acceleration value, prior to the toe marker's "x" directional stopping point. The algorithm for identification is given in Appendix D, the Combine.cpp program in the footDown subroutine. This program was interactive to ensure the proper ground contact point was selected for each trial. Visual examples of kinematic data, ground contact and stride length are given in Figure 7.

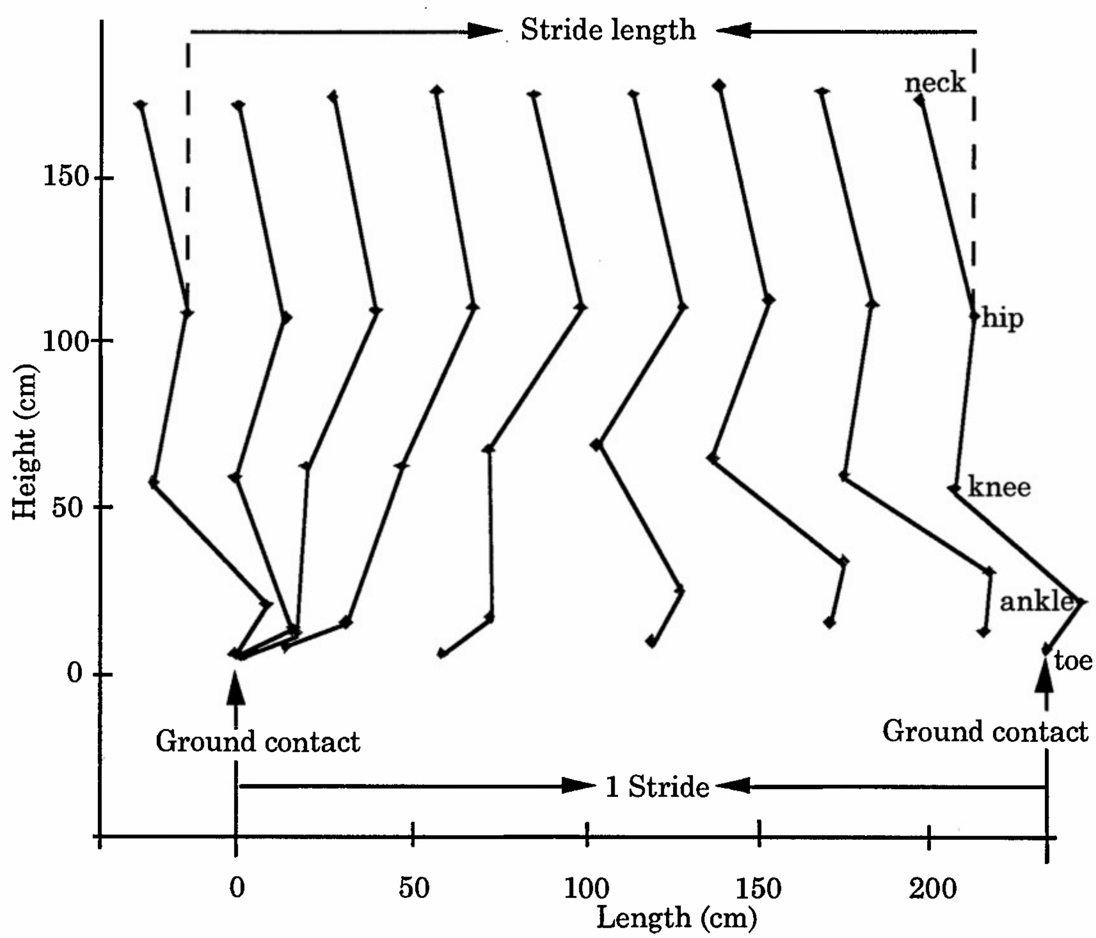

Figure 7. BR Displaying Ground Contact, One Stride and Stride Length.

Statistical Design and Analysis

Three repeated measures analyses of variance (ANOVAs) were used to evaluate group and dependent variable differences. The three BR conditions, (BRmax, BR_{80}, and BR_{60}) were compared to determine changes in the kinematic and kinetic parameters as BR velocity increased. The second comparison evaluated the differences between the two maximum velocity conditions (BRmax to FRmax). The third compared BRmax to FRequal in order to investigate similarities and differences between equal velocities for BR and FR. Level of significance was set at 0.05. Actual p values are reported for all results between $p = 0.10$ and $p = 0.001$. Values less than $p = 0.001$ are reported as $p < 0.001$. Correlation comparisons were made between different dependent variables such as BRmax and FRmax velocity. The dependent variables analyzed are given in Table 5. Data were analyzed using SYSTAT Version 5.2.

Since the BR conditions were percentages of the subject's maximum backward velocity (max, 80%, 60%), it was hypothesized that each dependent variable analyzed across the BR conditions would show a linear trend. Likewise, it was hypothesized that there would be a difference between the dependent variables across the BR conditions.

Table 5. List of Dependent Variables Analyzed for this Study

Category #	Category Title
1	Velocity
2	Maximum velocity of the foot during swing phase
3	Stride length
4	Intrinsic support length
5	Stride frequency
6	Stance time
7	Trunk angle at ground contact and toe-off
8	Hip range of motion
9	Knee range of motion
10	Ankle range of motion
11	Hip angular velocity at toe-off
12	Knee angular velocity at toe-off
13	Ankle angular velocity at toe-off
14	Vertical oscillation
15	Resultant impact peak (F1)
16	Time to resultant impact peak
17	Maximum impact loading rate
18	Resultant active peak (F2)
19	Time to resultant active peak
20	Initial anterior-posterior (A-P) peak
21	Final A-P braking force

Statistical analysis calculates the chance that two or more groups are different, not the chance that they are the same. This study not only sought to contrast the kinematic and kinetic parameters associated with backward running, but also to identify instances where parameters appeared to be similar. Some researchers (Thomas, Salazar, & Landers, 1991; Hreljac, 1992) have used the effect size, ES, to determine whether or not the difference between values is negligible. For this study, values being compared were considered similar if the effect size was 0.1 or less. ES values will be reported for ES $\leq$ 0.2. The following is the equation for effect size:

$$ES = (M_1 - M_2)/SD_{pooled}$$

CHAPTER IV

RESULTS AND DISCUSSION

The purpose of the study was to quantify the kinematic and kinetic parameters associated with backward running (BR). High velocity BR parameters were then compared to: (a) BR parameters at submaximal velocities, (b) forward running (FR) parameters at maximum velocity, and (c) FR parameters at a velocity equal to BRmax (FRequal). In addition, two groups were compared. One group was made up of individuals who used BR during athletic competition while the other group was comprised of individuals who ran as a form of exercise.

Results were reported on: (a) differences between dependent variables (Table 5) across conditions, (b) differences between groups across conditions, (c) interactions between groups and dependent variables, (d) linear trends, and (e) interactions within the linear contrast.

Velocity

All reported condition velocities are averages of three trials. However, FRequal, BR_{80} and BR_{60} target velocities were computed using the single fastest BRmax trial. Because of this, those values may be slightly greater than 100%, 80%, or 60% of the averaged BRmax. Group mean velocities for all group - conditions are given in Table 6.

Table 6. Mean Velocity in $m \cdot s^{-1}$

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	4.71±0.38	4.06±0.31	3.18±0.33	6.81±0.44	4.80±0.48
Elite	5.42±0.30	4.62±0.31	3.55±0.30	7.71±0.44	5.52±0.47

BRmax, BR_{80} and BR_{60} velocities were found to be significantly different, $F(2, 56) = 27.620$, $MSe = 6.762$, $p < 0.001$ and demonstrated a significant linear trend, $F(1, 28) = 961.082$, $MSe = 43.367$, $p < 0.001$. The Elite group performed all BR conditions at significantly faster velocities than the Athletic group, $F(1, 28) = 27.620$, $MSe = 6.762$, $p < 0.001$. FRmax velocities were significantly faster than BRmax velocities, $F(1, 28) = 678.57$, $MSe = 72.33$, $p < 0.001$. The Elite group recorded faster FRmax and BRmax velocities than the Athletic group, $F(1, 28) = 47.91$, $MSe = 9.77$, $p < 0.001$. There was not a statistically significant difference in velocity between the BRmax and FRequal conditions, $F(1, 28) = 2.290$, $p = 0.141$. The Elite group performed both BRmax and FRequal faster than the Athletic group, $F(1, 28) = 26.82$, $MSe = 7.704$, $p < 0.001$.

The BR condition comparisons indicated two important findings: (a) the individuals who used BR during athletic competition were faster at BR than the athletically active individuals, and (b) the testing protocol successfully created different linear BR conditions. It was hypothesized that the Elite group athletes would be more skilled at BR and would therefore perform BR faster than the Athletic group. The Elite group subjects were not only faster at BRmax, however, but at FRmax also. Comparing both groups' percentages of BR to FR velocity using an ANOVA showed no significant group differences, $F(1, 28) = 0.346$, $p = 0.561$. Overall, the Elite group's BR velocity was 70.4% of their FR velocity, whereas the Athletic group's was 69.3%. The highest BR to FR percentage was 79%, recorded by an individual in the Elite group. The lowest was 60%, recorded by a subject in the Athletic group. The concept that previous BR training by the Elite group would make them faster at BR may not be valid. It may have been the Elite group's sheer ability to run faster, forward or backward, that made them faster at BR.

Given a varied sample such as the entire population, FR velocity is likely a good predictor of BR velocity. Within select groups of trained individuals, such as the two groups examined in this study, however, FR velocity was not highly correlated with BR velocity. The R^2 for the Athletic and Elite groups were 0.196 and 0.031, respectively. Neither value explained a statistically significant portion of the variance. This point is important because the entire population does not need to become faster at BR, nor for that matter, does the Athletic group in this study. BR training would likely be for an elite group of athletes whose correlation of FR to BR would be small to non-existent.

There was no significant difference between BRmax and FRequal velocities. This statistical test did not indicate that the velocities were the same, but for the comparisons in this study, these two condition velocities (BRmax and FRequal) were considered equal.

Maximum Velocity of the Foot During Swing Phase

Maximum velocity of the foot during swing phase is an interesting parameter when comparing BR to FR. Values for this category indicate the fastest horizontal velocity recorded during each subject's swing phase. This can also be thought of as how fast the subject moved his foot forward to take the next step. This swing phase foot velocity was thought to be important because one of the limitations for running velocity regardless of direction might be the ability to move the foot forward fast enough to take the next stride. Maximum horizontal foot velocities are reported in Table 7.

Table 7. Maximum Foot Velocity in $m \cdot s^{-1}$

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	9.71±.0.91	8.34±0.70	6.64±0.58	12.05±1.49	8.39±0.74
Elite	11.26±0.60	9.56±0.70	7.78±0.84	12.92±0.94	10.26±1.03

Results showed significant increases in foot velocity as BR velocity increased, $F(2, 56) = 424$, $MSe = 80.45$, $p < .001$ and a linear trend, $F(1, 28) = 563$, $MSe = 160$, $p < 0.001$. The Elite group had consistently faster BR foot velocities than the Athletic group, $F(1, 28) = 31.08$, $MSe = 38.3$, $p < 0.001$. The FRmax condition showed a greater maximum swing phase foot velocity than the BRmax condition, $F(1, 28) = 91.508$, $MSe = 60.10$, $p < 0.001$. The Elite group had faster swing phase foot velocities than the Athletic group, $F(1, 28) = 14.689$, $MSe = 22.02$, $p = 0.001$. Maximum foot velocities during swing phase of the FRequal condition were less than those for the BRmax condition, $F(1, 28) = 80.466$, $MSe = 20.22$, $p < 0.001$. The Elite group had greater swing phase foot velocities than the Athletic group, $F(1, 28) = 43.84$, $MSe = 38.11$, $p < 0.001$.

The hypothesis that swing phase foot velocity is a limiting factor in a subject's overall velocity would predict that the maximum foot velocities of FRmax and BRmax would be similar. This was not found to be the case. Swing phase foot velocity did not appear to limit maximum velocity. An alternate possibility, that foot velocities between BRmax and FRequal would be similar was also refuted.

Overall, swing phase foot velocity was a better predictor of BR velocity than it was of FR velocity. It was also a better predictor of the Athletic group's velocity than the Elite group's. Correlation results of swing phase foot velocity to BRmax and FRmax are given in Table 8.

Table 8. R^2 Values of Swing Phase Foot Velocity to Running Speed

Group	BRmax	FRmax
Athletic	0.848	0.603
Elite	0.729	0.512

Stride Length

Stride length was calculated by measuring the horizontal change in hip marker position between two sequential ground contacts of the designated foot (Figure 7). There is published literature on stride length for fast velocity FR conditions, but no research on BR stride length at fast velocities. Because of this, the maximum length of a BR stride was unknown. Table 9 contains group stride length means for all conditions.

Table 9. Stride Length Means in cm

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	239±28.7	228±25.9	211±26.3	388±32.8	360±27.5
Elite	261±33.9	260±33.5	223±27.8	402±22.1	379±20.9

Results showed significant increases in BR stride length as velocity increased, $F(2, 56) = 44.3$, $MSe = 8861$, $p < .001$ and a linear trend, $F(1, 28) = 56$, $MSe = 15609$, $p < 0.001$. The Elite group had consistently longer BR stride lengths than the Athletic group, $F(1, 28) = 4.855$, $MSe = 10776$, $p = .036$. A significant interaction was seen between groups, $F(2, 56) = 3.698$, $MSe = 744.2$, $p = 0.031$.

FRmax stride length was significantly longer than BRmax stride length, $F(1, 28) = 503$, $MSe = 317286$, $p < 0.001$. The Elite group demonstrated a tendency towards longer stride length across the maximum velocity conditions, ($F(1, 28) = 4.076$, $MSe = 4678$, $p = 0.053$). The Elite group showed an 8.0% greater stride length for the BRmax condition, but only a 3.4% greater stride length for the FRmax condition. FRequal stride length was longer than BRmax stride length, $F(1, 28) = 311$, $MSe = 216{,}052$, $p < 0.001$. The Elite group had significantly longer stride lengths than the Athletic group across the equal velocity conditions, $F(1, 28) = 6.94$, $MSe = 6200$, $p = .014$.

The Elite group's stride length did not change significantly between the BRmax and BR_{80} conditions. The Athletic group's did. The Elite group's results were similar to reported FR findings (Mero, Komi & Gregor, 1992), whose authors noted that in FR, stride length increased until velocity approached 7 $m \cdot s^{-1}$, after which increases in stride length were small. The Elite group in this study displayed this stride length plateauing. At exactly what percent of maximum velocity this occurred was beyond the scope of this study, though results indicate the Elite group's stride length plateaued at between 60 and 80 percent of maximum velocity. It is not known why the Athletic group did not display this same trend, but instead continued to increase stride length as velocity increased. The Athletic group might not have reached the anatomical limit to their stride length at the speeds they were able to produce.

Group stride length differences were greater in BR than FR. This result was expected since the Athletic group was equally experienced at FR while the Elite group was uniquely experienced at BR.

Intrinsic Support Length (ISL)

Intrinsic support length (ISL) was calculated by summing the horizontal distances from the body's center of gravity to the toe at ground contact (GC) and toe-off (TO) (Nilsson, Thorstensson, & Halbertsma, 1985). In this study, the hip marker was used to represent the center of gravity. Examples of how hip to toe measurements were obtained for BR and FR are shown in Figure 8.

Data between subjects of different heights and leg lengths were normalized and reported as a percent of total leg length. Mean values for horizontal distances between toe and hip markers for ground contact and toe-off across all conditions are reported in Table 10.

Table 10. Horizontal Distance Between Toe and Hip during Ground Contact (GC) and Toe-Off (TO) and Total ISL (in % Leg Length)

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic GC	28.8±8.70	28.0±7.37	27.6±9.15	41.3±5.51	43.6±5.45
Elite GC	22.0±7.43	28.4±8.58	25.1±9.75	38.8±5.92	41.9±4.88
Athletic TO	43.1±4.73	42.0±4.88	42.5±3.93	54.4±9.74	46.9±7.95
Elite TO	48.4±5.52	47.1±6.97	47.6±8.45	54.5±9.77	47.5±9.98
Athletic ISL	72.0±7.74	70.0±7.49	70.1±11.2	95.8±12.1	90.5±7.52
Elite ISL	70.5±8.48	75.4±5.48	72.7±9.17	93.3±11.8	89.5±10.8

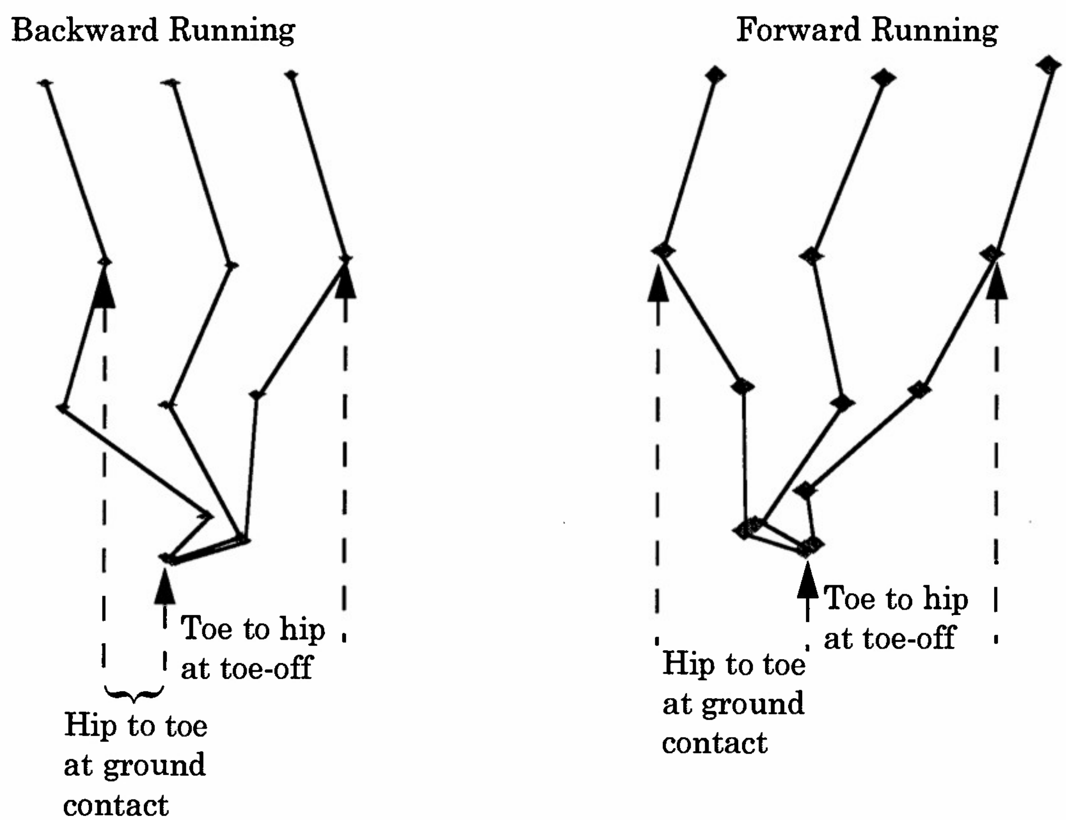

Figure 8. Intrinsic Support Length Measurements at Ground Contact and Toe-Off During BR and FR.

Hip to toe distances at ground contact and toe off were investigated for the BR conditions. There were no significant condition or group differences at ground contact. There was a group interaction in percent lengths across the three conditions, $F(2, 56) = 3.913$, $MSe = 97.910$, $p = 0.026$, along with a quadratic trend, with the BR_{80} values longer than the other BR conditions, $F(1, 28) = 8.326$, $MSe = 105.310$, $p = 0.007$. This interaction was further evaluated, revealing significantly shorter hip to toe ground contact distances, $F(1, 28) = 5.\ 345$, $MSe = 349$, $p = 0.028$ for the Elite group.

There were no significant condition differences in the hip to toe distances at toe-off for the BR conditions. There was a group difference, with the Elite group producing longer distances than the Athletic group, $F(1, 28) = 6.573$, $MSe = 590.951$, $p = 0.016$. When the hip to toe distances at ground contact and toe-off were combined to form the intrinsic support length, BR showed no statistical differences between conditions.

The comparison of hip to toe distances at ground contact between FRmax and BRmax revealed shorter distances for the Elite group, $F(1, 28) = 5.94$, $MSe = 329.9$, $p = 0.021$. FRmax distances were greater than BRmax distances, $F(1, 28) = 74.75$, $MSe = 3186$, $p < 0.001$. The comparison of hip to toe distances at toe-off showed no significant group differences, however, a condition difference was observed, with FRmax distance values being greater, $F(1, 28) = 19.8$, $MSe = 1133$, $p < 0.001$.

The comparison of hip to toe distances at ground contact for FRequal and BRmax revealed significantly longer FRequal distances, $F(1,28) = 125$, MSe = 4478, $p < 0.001$. Again, the Elite group distances were shorter than the Athletic group distances, $F(1, 28) = 4.737$, MSe = 267.2, $p = 0.038$. The comparison of hip to toe distances at toe-off showed no group or condition differences, suggesting that this variable might be related more to velocity than direction.

These BR intrinsic support length findings demonstrate two points. First, there was a clear difference between groups. The Elite group had a shorter BRmax distance at ground contact and a longer BRmax distance at toe-off than the Athletic group (all Elite distances were greater than the greatest Athletic distance). A shorter hip to toe distance at ground contact could mean less braking force and indicate a more active ground contact. Previous research supports this idea. Kunz and Kaufmann (1981) found that elite sprinters had shorter hip to toe distances at ground contact than a group of elite decathletes. On the other end, a greater distance from hip to toe at toe-off could allow for greater force generation during push-off. These observed differences between the Elite and Athletic groups for these variables are therefore consistent with the increased velocity of the Elite group and might be a teachable technique to increase BR velocity.

Second, there was no significant change in intrinsic support length (ISL) with increased velocity. This is contrary to reported FR results. A Nilsson, Thorstensson, and Halbertsma (1985) study of ten male subjects showed increasing ISL as running velocity increased from 1 to 8 $m \cdot s^{-1}$. Increases in velocity are often accompanied by increases in stride length (Mero et al., 1992). Results in this study indicate that BR stride length was not increased (from 60% to 100% of maximum velocity) via an increased ISL, however, suggesting that stride length and ISL were not closely related in BR and that subjects were able to increase their stride length via some other method, such as increased horizontal force generation.

The hip to toe distance at toe-off findings for both FRmax and BRmax suggest a "longer support--greater velocity" relationship. Since a runner can only produce force while his foot is in contact with the ground, it is logically assumed that a greater velocity can be generated from a longer hip to toe distance at toe-off (longer ISL TO). This concept is also supported by Nilsson et al. (1985). In this study, the FRmax condition exhibited longer distances and faster velocities than the BRmax condition, and the Elite group displayed longer distances and faster velocities than the Athletic group, while at equal velocities, hip to toe distances at toe-off were not statistically different. One ISL constancy between BR and FR was that faster running coincided with a slightly shortened distance between hip and ground contact (at least from 60% through maximum velocity).

Stride Frequency

Stride frequency is the number of strides taken per unit of time. Stride frequency was determined by measuring the time from first foot contact with the force platform to the subsequent contact of the same foot. This number was converted to strides per minute. The mean stride frequencies for all group - conditions are given in Table 11.

Table 11. Stride Frequency Means (in Strides per Minute)

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	120.8±14.3	108.9±11.5	91.6±8.92	106.9±11.3	83.4±4.97
Elite	127.8±14.5	109.4±14.8	97.2±12.5	116.6±9.82	93.7±8.76

Stride frequency significantly increased with BR velocity, $F(2, 56) = 172.3$, MSe = 6701, $p < 0.001$. This increase produced a significant linear trend, $F(1, 28) = 123.576$ MSe = 20633, $p < 0.001$. There were no stride frequency group differences for BR, $F(1, 28) = 1.011$, $p = 0.323$.

BRmax stride frequency was significantly greater than FRmax stride frequency, $F(1, 28) = 25.313$, MSe = 2397.682, $p < 0.001$. The Elite group exhibited greater stride frequencies than the Athletic group, $F(1, 28) = 4.699$, MSe = 1055.8, $p = 0.039$. BRmax stride frequency was also greater than FRequal stride frequency, $F(1, 28) = 182$, MSe = 18132, $p < 0.001$. Again, the Elite group showed greater stride frequencies than the Athletic group, $F(1, 28) = 8.712$, MSe = 1385.9, $p = 0.006$.

Contrary to the researcher's expectation there were no group differences in BR stride frequencies. The observed group difference between BR and FR, therefore, could have been an anatomical and not a training effect. The Elite group consisted of sprinters (likely having predominately fast twitch fibers) that were also performing an anaerobic task protocol, leading to the hypothesis that the Elite group would have greater stride frequencies. This was only the case, however, when the FR data was factored into the analysis. Velocity is comprised of stride length times stride frequency. The Elite group had significantly faster BR velocities and longer stride lengths, but not greater stride frequencies. These results indicate that it was predominately stride length that differentiated between the velocities of the two groups.

Prior to this study, it was not known whether stride frequencies differed between backward and forward maximum velocities. This researcher's hypothesis was that each person had a maximum stride frequency capability, a quasi-motor program for stride frequency, whether running backward or forward. The results from this study do not support this hypothesis, since stride frequency was statistically different for BRmax versus FRmax and BRmax versus FRequal.

Stance Time

Stance time is the portion of the stride during which the foot is in contact with the running surface. It is during this portion of the stride that force is produced and velocity is attained. Stance time was determined using force platform data and defined as the time during which a force greater than 20 N was being generated. Stance time is a portion of stride time. In order to compare stance time across different stride times, stance time was reported as a percentage of stride time. Group stance times for all conditions are given in Table 12.

Table 12. Stance Time Means as a Percentage of Stride Time

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	31.9±2.91	33.3±2.79	37.4±3.25	27.0±2.73	27.1±1.67
Elite	29.5±2.67	30.7±3.35	34.7±4.68	25.9±2.85	26.1±2.25

BR stance time as a percentage of stride time significantly decreased as velocity increased, $F(2, 56) = 56.64$, $MSe = 0.023$, $P < 0.001$. The BR trend was linear, $F(1, 28) = 70.96$, $MSe = 0.043$, $p < 0.001$. The Elite group had significantly shorter stance times than the Athletic group, $F(1, 28) = 5.890$, $MSe = 0.015$, $p = 0.022$. BRmax stance time as a percentage of stride time was significantly greater than FRmax stance time, $F(1, 28) = 43.48$, $MSe = 0.026$, $p < .001$. The Elite group's maximum velocity stance times were significantly less than the Athletic group's, $F(1, 28) = 5.552$, $MSe = 0.005$, $p = 0.026$. FRequal stance time as a percentage of stride time was less than BRmax stance time, $F(1, 28) = 38.07$, $MSe = 0.024$, $p < 0.001$, and the Elite group had a significantly less time than the Athletic group, $F(1, 28) = 9.922$, $MSe = 0.005$, $p = 0.004$.

BR stance time as a percentage of stride time decreased as velocity increased. FR stance time, however, did not appear to change across the two velocities (FRmax and FRequal). An effect size analysis was conducted, $ES = 0.05$, confirming there was no stance time (as a percentage of stride time) change. Therefore, this is a clear difference between BR and FR. Threlkeld et al. (1989) determined that actual stance time for BR was 10% shorter than for FR. This study's results indicate that actual BRmax stance time was 18% shorter than FRequal. The BR to FR velocities of this study and the Threlkeld et al. study were different, and given the tendencies seen in both FR and BR stance time as velocity increases, the Threlkeld et al. results appear to be consistent with this study's results. Overall, the results indicate the runners spent a greater percentage of time on the ground per stride during BR compared to FR.

The Elite group had significantly shorter stance times as percentages of stride times than the Athletic group across all comparisons. The group differences may have been due to the differences in velocity between the two groups.

Trunk Angle

Trunk angles were measured between the trunk and the vertical axis. Trunk angles to the left of the vertical axis are given as negative values (i.e. -5° instead of 355°). Examples of BR and FR trunk angles are shown in Figure 9.

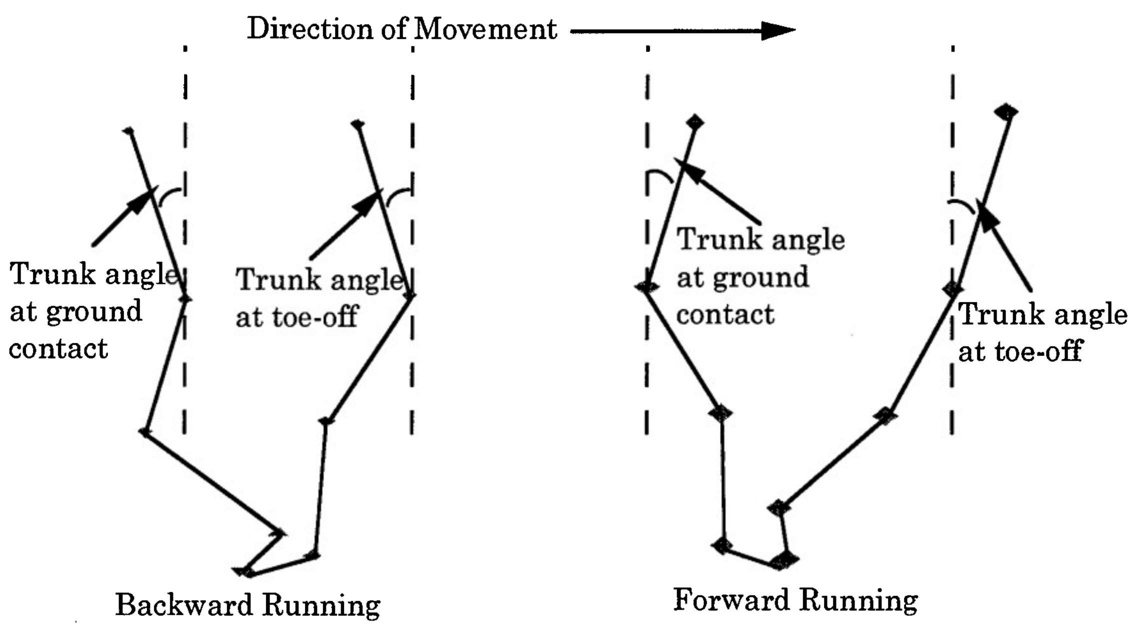

Figure 9. Trunk Angle Measurements For BR and FR.

Trunk angles were recorded at ground contact and toe-off. Changes in trunk angle between ground contact and toe-off were calculated for comparisons of BR and FR trunk stability (less change meaning greater stability) and determination of within groups differences. Absolute values of BRmax trunk angles were compared to FRmax and FRequal trunk angles. Mean trunk angles for all group - conditions are given in Table 13.

Table 13. Trunk Angle in Degrees at Ground Contact (GC) and Toe-Off (TO)

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic GC	-13.73±12.3	-7.90±8.32	-4.05±7.31	14.65±5.86	9.12±5.16
Elite GC	-18.53±10.6	-14.99±11.4	-12.49±12.7	19.55±4.08	14.77±4.75
Athletic TO	-11.70±11.1	-6.66±7.29	-4.05±6.39	16.76±5.15	13.39±5.05
Elite TO	-15.25±11.1	-12.46±11.5	-9.37±12.5	17.74±4.05	15.27±3.79
Athletic GC-TO	3.49±2.52	2.85±2.06	2.09±4.81	3.34±1.89	4.47±2.81
Elite GC-TO	3.27±1.78	2.63±1.87	3.12±2.68	2.61±1.81	2.39±1.90

Significant increases in trunk angle (larger absolute values) were observed as BR velocity increased at both ground contact, ($F(2, 56) = 21.37$, $MSe = 469.268$, $p < 0.001$) and toe-off, ($F(2, 56) = 25.47$, $MSe = 346.55$, $p < 0.001$. These increases were linear at both ground contact, ($F(1, 28) = 23.97$, $MSe = 927.166$, $p < 0.001$) and toe-off, ($F(1, 28) = 34.324$, $MSe = 687.358$, $p < 0.001$). The Elite group demonstrated a tendency toward greater trunk angles at ground contact, $F(1, 28) = 3.49$, $MSe =1034.3$, $p = 0.072$, but not at toe-off, $F(1, 28) = 1.829$, $p = 0.187$, compared to the Athletic group.

There was a statistically similar ($ES \leq 0.1$) anterior trunk angle in the BRmax and FRmax conditions at ground contact, $(1, 28) = 0.087$, $p = 0.770$, $ES = 0.07$. The Elite group demonstrated a tendency towards greater trunk angles at ground contact, $F(1,28) = 4.001$, $MSe = 306$, $p = 0.055$. There were no maximum velocity condition or group differences at toe-off.

BRmax produced significantly greater anterior trunk angles than FRequal at ground contact, $F(1,28) = 4.342$, $MSe = 305$, $p = 0.046$. The Elite group exhibited a significantly greater trunk angle than the Athletic group, $F(1, 28) = 4.718$, $MSe = 359$, $p = 0.038$. BRmax and FRequal trunk angles at toe-off were near identical, $F(1, 28) < 0.001$, $p = 0.998$, $ES < 0.001$. The two groups' BRmax and FRequal trunk angles were not statistically different at toe-off.

Subjects demonstrated a tendency towards greater trunk angle change as BR velocity increased, $F(2, 56) = 2.995$, $p = 0.058$. This tendency neared significance, $F(1, 28) = 3.726$, $p = 0.064$. The groups were similar in trunk angle change over one stride, $F(1,28) = 0.086$, $ES = 0.092$.

BRmax and FRmax demonstrated no significant condition or group differences in trunk angle change over the stance phase. BRmax and FRequal trunk angle changes appeared similar, $F(1,28) = 0.007$, $ES = 0.019$. The Elite group exhibited less trunk angle change between FRequal ground contact and toe-off than the Athletic group, $F(1, 28) = 5.686$, $p = 0.024$.

Kunz and Kaufmann (1981) found that elite sprinters exhibited greater trunk angles than decathletes. In this study, the Elite group was therefore expected to have a greater trunk angle during FR than the Athletic group.

Furthermore, during BR, the Elite group was expected to have a greater body lean due to a training difference. Most of the Elite group were defensive backs in football that had been taught to lean to facilitate quick changes in direction.

Since the Elite group showed both greater BR velocity and greater trunk angle than the Athletic group, one might conclude that increased trunk angle in BR aided in increasing BR velocity. It is possible, though, that increased body lean is a natural phenomenon that occurs as BR velocity increases. The mean values from the FR condition indicate that body lean increased with FR velocity as well, suggesting a similarity between the two directions of running. However, body lean during FR was in the direction of movement, while during BR, it was away from the direction of movement.

Trunk angles appeared to undergo greater changes between ground contact and toe-off during the higher velocity conditions. The Elite group tended to change trunk angle less during a stride than the Athletic group, though mostly during the FR conditions. Overall, there was little difference in stance phase trunk angle change between FR and BR.

Hip Range of Motion

Hip range of motion was measured from the hip's position of maximum extension to its position of maximum flexion during the stride. Hip ROM data are given in Table 14.

Table 14. Hip ROM in Degrees

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	41.75±8.58	38.80±6.91	39.41±7.80	68.36±6.05	60.50±4.43
Elite	41.87±10.80	39.42±8.33	38.35±7.47	70.15±3.28	64.91±5.32

There was a significant increase in hip ROM as BR velocity increased, $F(2, 56) = 3.320$, MSe = 79.7, $p = 0.043$, with similar values for both groups $F(1, 28) = 0.002$, ES = 0.013. The data showed a tendency toward a linear trend, $F(1, 28) = 3.28$, $p = 0.081$. Hip ROM was significantly greater during FRmax than BRmax, $F(1, 28) = 195$, MSe = 11298, $p < 0.001$, with no difference between the groups, $F(1, 28) = 0.222$, ES = 0.06. Hip ROM was greater for FRequal compared to BRmax., $F(1, 28) = 117.5$, MSe = 6545, $p < 0.001$. BRmax to FRequal group comparisons showed no significant differences.

This investigator expected increases in hip ROM with increases in BR velocity because of the longer stride lengths often associated with increased velocity. Hip ROM did increase with velocity, most changes occurring between the 80% and maximum BR conditions. While the Elite group showed a linear trend, the Athletic group did not. Thus, there was no overall linear trend.

A reason behind testing both BR and FR was to evaluate similarities and differences, especially in joint movements. Hip ROM during high speed BR and FR is visually different. Therefore, the findings of a greater ROM in both FRmax and FRequal than BRmax was expected. Overall, hip ROMs were 166% and 133% greater in FRmax and FRequal than BRmax, respectively.

Along with maximum and minimum hip angles, this study also determined when during the stride these angles occurred. In BR, maximum hip extension occurred just prior to ground contact and maximum hip flexion occurred prior to the swing phase midpoint. The relative times that maximums and minimums occurred did not change as the subject's velocity changed.

The groups were similar in hip ROM for the BR and FR conditions, and especially so throughout the different velocities of BR. Hip ROM did increase slightly with BR effort, but did not appear to be a reason the Elite group performed at faster velocities than the Athletic group.

Knee ROM

Knee range of motion was measured from the knee's position of maximum extension to its position of maximum flexion during one stride. Knee ROM data are given in Table 15.

Table 15. Knee ROM in degrees

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	79.64±12.5	76.32±12.3	76.10±13.1	120.4±15.7	117.3±11.1
Elite	86.54±11.8	83.17±14.9	81.70±15.2	114.1±12.7	120.1±13.2

There was a significant increase in BR knee ROM as velocity increased, $F(2, 56) = 4.16$, $MSe = 147.67$, $p = 0.21$. This increase was linear, $F(1, 28) = 4.680$, $MSe = 263$, $p = 0.039$. No group differences were found.

There was a significantly greater knee ROM in the FRmax condition than the BRmax condition, $F(1, 28) = 105.581$, $MSe = 17532$, $p < 0.001$. Group differences were hidden in the significant interaction between the groups and conditions, $F(1, 28) = 4.001$, $MSe = 664.402$, $p = 0.05$. The Elite group demonstrated a greater knee ROM during BRmax than the Athletic group, while the Athletic group showed a greater knee ROM during FRmax than the Elite group.

There was a significantly greater knee ROM during FRequal than during BRmax, $F(1, 28) = 159.03$, $MSe = 18974$, $p < 0.001$. The group differences approached significance, with the Elite group showing greater knee ROM than the Athletic group, $F(1, 28) = 3.102$, $p = 0.089$.

Along with maximum and minimum angles, this study also determined when during the stride these angles occurred. In BR, maximum knee extension occurred at toe-off and maximum knee flexion occurred near the swing phase midpoint. The relative times that maximums and minimums occurred did not change as the subject's velocity changed. Both group's knee ROMs increased as BR velocity increased, indicating that ROM of the knee is an important factor in increasing BR velocity. Interestingly, though, while the Elite group's BR knee ROM showed a linear increase with velocity, their stride length topped off at BR_{80}. This could indicate that knee ROM during BR is not a factor of increased stride length at the faster velocities.

The Athletic group had a greater FRmax knee ROM than the Elite group, (120° vs. 114°). This was unexpected, since the Elite group had both a longer FRmax stride length and a faster FRmax velocity. This could indicate the knee ROM is not indicative of increased stride length in FR either.

Ankle ROM

Ankle ROM was measured from the ankle's position of maximum extension to its position of maximum flexion during one stride. Ankle ROM data are given in Table 16.

Table 16. Ankle ROM in Degrees

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	46.20±6.05	44.63±7.26	46.57±5.58	52.07±8.97	54.38±11.5
Elite	43.70±3.35	44.38±8.61	42.09±6.46	50.76±10.1	53.93±13.2

Ankle ROM was similar across the BR conditions, $F(2, 56) = 0.244$, $p = 0.784$, $ES = 0.07$. There were no significant BR group differences. FRmax had a significantly greater ankle ROM than BRmax, $F(1, 28) = 17.98$, $MSe = 627$, $p = 0.001$ and there were no significant group differences across the maximum velocity conditions. FRequal had a significantly greater ankle ROM than BRmax, $F(1, 28) = 190.0$, $MSe = 1270$, $p < 0.001$ and there were no significant group differences across the equal velocity conditions.

Along with maximum and minimum ankle angles, this study also determined the relative time that these angles occurred. In BR, maximum ankle extension occurred at toe-off and maximum ankle flexion occurred at approximately one third of the stance phase. The relative times that maximums and minimums occurred did not change as the subject's velocity changed.

Comparisons of ankle ROM did not appear to highlight many differences. Ankle ROM stayed constant as BR velocity increased from 60% to 100%. There was no statistical difference between the ankle ROM of the two groups.

Hip Angular Velocity at Toe-Off

Hip angular velocity is the rate of change in hip angular position. Positive values indicate the hip joint was extending, while negative values indicate the hip joint was in flexion. Hip angular velocity data are given in Table 17.

Table 17. Hip Angular Velocity at Toe-Off in Degrees • s^{-1}

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	337±137	198±105	93±107	269±76.7	-263±88.1
Elite	395±158	234±158	151±121	311±98.4	-202±108

Hip angular velocity at toe-off increased significantly with increased BR velocity, $F(2, 56) = 88.17$, MSe = 454462, $p < 0.001$. This increase was linear, $F(1,28) = 105.05$, MSe = 893562, $p < 0.001$. There were no significant group differences.

BRmax hip angular velocity at toe-off was significantly greater than FRmax hip angular velocity, $F(1, 28) = 7.72$, MSe = 86760, $p = 0.010$. There were no significant group differences in the maximum velocity conditions.

BRmax and FRequal angular velocities were not compared since comparisons of the numbers would be confounded by the difference in direction. However, given the fact the trunk remains relatively stable, the difference in signs between the two FR conditions indicates that the distal end of the thigh is moving in different directions at toe-off. In FRmax, the distal end of the thigh is still moving in the posterior direction (opposite of movement). In FRequal, it is moving anteriorly (in the direction of movement). In all BR conditions, the distal end of the thigh is moving posteriorly at toe-off (in the direction of movement).

The linear increase in hip angular velocity during the BR conditions indicates that as velocity increased, the hip initiated a faster movement through swing phase. This was consistent with the faster stride frequencies as velocity increased.

Knee Angular Velocity at Toe-Off

Knee angular velocity is the rate of change in knee angular position. Positive values indicate the knee joint was extending, while negative values indicate the knee joint was in flexion. Due to varied knee positions during FR, no generalizations were made as to direction of shank movement with positive or negative angular velocity. For BR, positive knee angular velocities indicated the knee was extending the shank opposite to the direction of movement. Knee angular velocity data are given in Table 18.

Table 18. Knee Angular Velocity at Toe-Off in Degrees • s^{-1}

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	98.0±137	85.6±105	67.5±107	-131.8±206	371.0±97.7
Elite	96.7±158	100.5±159	92.1±122	-238.2±156	464.9±77.7

There were no significant differences in knee angular velocity during the BR conditions, $F(2, 56) = 1.399$, $p = 0.255$ and no BR group differences in knee angular velocity. Comparisons were not made between BRmax and FRmax due to the difference in angular velocity direction. FRequal had a significantly greater angular velocity than BRmax, $F(1, 28) = 265.73$, MSe = 1541977, $p < 0.001$ and there was a group difference, $F(1, 28) = 4.755$, MSe = 32119, $p = 0.038$, due to the Elite group's significantly higher FRequal knee angular velocity.

BR knee angular velocity at toe-off did not significantly change as velocity increased. This result is consistent with the fact that knee ROM did not change. FRequal angular velocities at toe-off were varied, with some subjects performing knee extension while others were in knee flexion.

Ankle Angular Velocity at Toe-Off

Ankle angular velocity is the rate of change in ankle angular position. Positive values indicate the ankle joint was plantarflexing, while negative values indicate the ankle joint was in dorsiflexion. Due to varied ankle positions during FR as well as foot contact with the ground during both BR and FR, no generalizations were made as to direction of foot movement with positive or negative angular velocity. Ankle angular velocity data is given in Table 19.

Table 19. Ankle Angular Velocity at Toe-Off in Degrees • s^{-1}

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	577.2±74.3	541.0±63.8	497.6±55.2	862.5±190	711.4±115
Elite	562.1±63.1	468.1±61.8	369.6±62.3	866.6±212	700.2±156

Ankle angular velocity increased significantly as BR velocity increased, $F(2, 56) = 10.45$, MSe = 138777, $p < 0.001$. This trend was linear, $F(1,28) = 14.823$, MSe = 277382, $p < 0.001$. There were no significant group differences.

FRmax had a significantly higher ankle angular velocity than BRmax, $F(1, 28) = 44.33$, MSe = 1304814, $p < 0.001$. The groups' ankle angular velocities for the maximum velocity comparison were similar, $F(1,28) = 0.013$, $p = 0.910$, ES = 0.02. FRequal had a significantly higher ankle angular velocity than BRmax, $F(1, 28) = 13.42$, MSe = 278214, $p = 0.001$. The groups' ankle angular velocities for the equal velocity comparison were similar, $F(1, 28) = 0.121$, $P = 0.730$, ES = 0.08.

Unlike hip and knee angular velocity, ankle angular velocity at toe-off was comparable between BR and FR. In both BR and FR, the ankle was plantar flexing at toe-off. This plantar flexion was consistent during each of the five conditions and across both groups in the study. The results of ankle angular velocity indicate that BR and FR values increased with increased velocity and that FR values were larger than BR values at equal effort and velocity.

Vertical Oscillation

Vertical oscillation refers to the vertical distance the hip marker traveled during a stride from its lowest to its highest point and is meant to represent the vertical change in the body's center of mass during a stride. Hip vertical oscillation values are given in Table 20. An example of hip vertical oscillation is given in Figure 10.

Table 20. Vertical Oscillation Across One Stride (cm)

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	4.30±1.36	5.04±1.09	6.54±1.43	2.40±0.73	4.56±1.31
Elite	3.12±0.48	4.40±0.89	5.61±1.08	2.83±1.00	3.59±1.45

Vertical oscillation during BR decreased significantly as velocity increased, $F(2, 56) = 68.6$, $MSe = 42.2$, $p < 0.001$. This trend was linear, F(1, 28) = , $MSe = 83.7$, $p < 0.001$. The Elite group had significantly less vertical oscillation than the Athletic group, $F(1, 28) = 7.9$, $MSe = 18.9$, $p = 0.009$.

FRmax showed significantly less vertical oscillation than BRmax, $F(1, 28) = 25.6$, $MSe = 18.1$, $p < 0.001$. There was a significant interaction between groups, F(1, 28) = 13.9, MSe = 9.8, p = 0.001. The Elite group's FRmax vertical oscillation was 91% of its BRmax value, while the Athletic group's FRmax vertical oscillation was 55% of its BRmax value.

There was no statistical difference between the vertical oscillations of BRmax and FRequal, F(1, 28) = 1.95, p = 0.17. However, their ES value was greater than the cutoff of 0.1, indicating the conditions were not statistically similar. The Elite group had significantly less vertical oscillation than the Athletic group, F(1, 28) = 8.9. MSe = 17.3, p = 0.006.

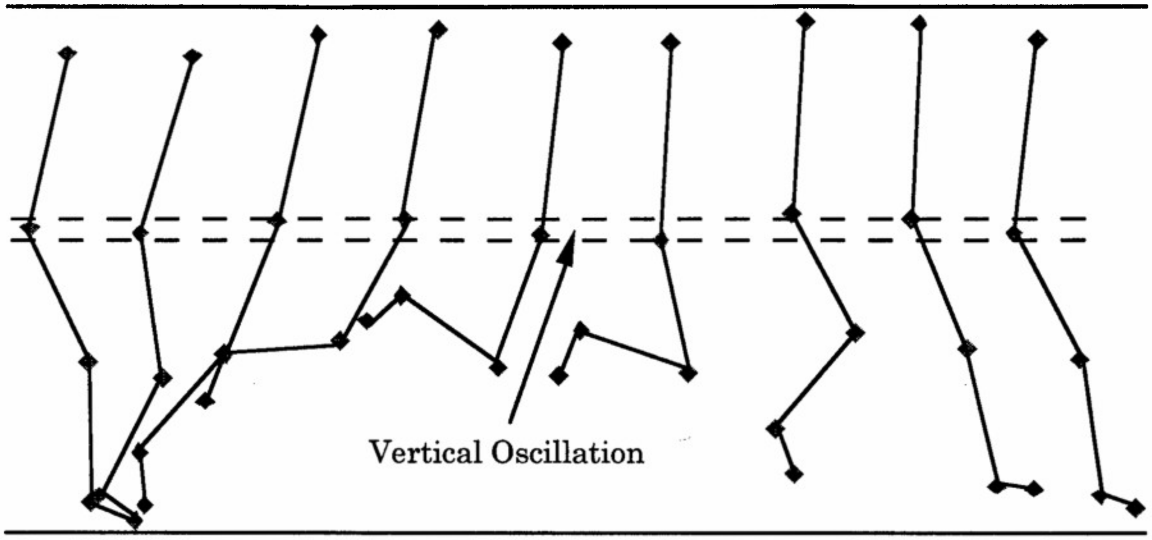

Figure 10. Hip Vertical Oscillation Over a Stride of FR.

The faster the running velocity (BR and FR), the less vertical oscillation the individual exhibited over a stride length. Mann and Hagy (1980) noted that the body's center of mass lowered as velocity increased.

This lowering and less vertical oscillation are likely related, both results of change in the projectile motion of the human body.

The results indicate that equal velocities of BR and FR have vertical oscillation values that are not significantly different. During FRequal, the subjects had some freedom to change their vertical oscillations. During BRmax, the subjects did not because the maximum effort dictated only one method of completing the task. This difference could have been the reason that these two conditions were not equal.

Resultant Impact Peak

The resultant impact peak was recorded as the highest resultant vertical and A-P force within the first 20% of stance time. Resultant impact peak values are given in Table 21.

Table 21. Resultant Impact Peak in Body Weight (BW)

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	1.43±0.29	0.99±0.33	0.49±0.29	2.19±0.79	2.05±0.49
Elite	1.85±0.60	1.17±0.50	0.74±0.35	2.32±0.88	1.90±0.72

Resultant impact peaks increased significantly as BR velocity increased, $F(2, 56) = 126.7$, $MSe = 7.89$, $p < 0.001$. This increase was linear, $F(1, 28) = 185.2$, $MSe = 15.75$, $p < 0.001$. The Elite group had significantly greater BR resultant impact peaks than the Athletic group, $F(1, 28) = 4.78$, $MSe = 1.80$, $p = 0.037$.

FRmax resultant impact peaks were greater than BRmax resultant impact peaks, $F(1, 28) = 10.5$, $MSe = 5.76$, $p = 0.003$ and the Elite group demonstrated a tendency towards greater resultant impact peaks in the maximum velocity conditions than the Athletic group, $F(1, 28) = 3.097$, $p = 0.089$,. FRequal resultant impact peaks were also significantly greater than BRmax resultant impact peaks, $F(1, 28) = 4.99$, $MSe = 1.71$, $p = 0.034$. There was no equal velocity group difference, though the two groups showed a tendency towards interaction, $F(1, 28) = 3.591$, $p = 0.068$. This was due to a large resultant impact peak increase from BRmax to FRequal in the Athletic group, while the Elite group values changed little.

Physical therapists have been using BR for years in the belief that BR has lower impact forces than FR. Threlkeld et al. (1989) was the only BR study to show any vertical force data. These researchers noted that the initial impact peak normally seen during FR was "markedly attenuated" in their BR condition. That study's 3.5 $m \cdot s^{-1}$ was approximately the velocity of the BR_{60} condition for the Athletic and Elite groups in this study. This study used resultant impact peaks that should be a better indicated of true force. As seen in Figure 11 (Representative Ground Reaction Forces (GRF) for the

Three BR Conditions), the BR_{60} condition had a visible resultant impact peak. As velocity increased, BR resultant impact peaks appeared similar to FR resultant impact peaks (Figure 12). Thus, the belief that BR has attenuated resultant impact peaks was not supported from the data collected during any of the three BR velocity conditions. Depending on the individual, BR resultant impact peaks can be similar to those of FR at the same velocity.

The group difference seen during the BR conditions may not be due to different techniques or styles of the groups, but to the faster speed of the Elite group. Since there was a condition difference with velocity, it would stand to reason that a group running at a faster velocity would record greater impact forces.

Because the Elite group's BRmax and FRequal resultant impact peaks appeared similar, an effect size was calculated on just the Elite group between the conditions. The Elite group did have similar resultant impact peaks in the BRmax and FRequal conditions, ES = 0.08. Thus, impact peaks may be a result of velocity and not the direction of movement as was seen with the Elite group results. Resultant impact peak data indicate that the use of BR to reduce impact forces should be conducted at slower velocities.

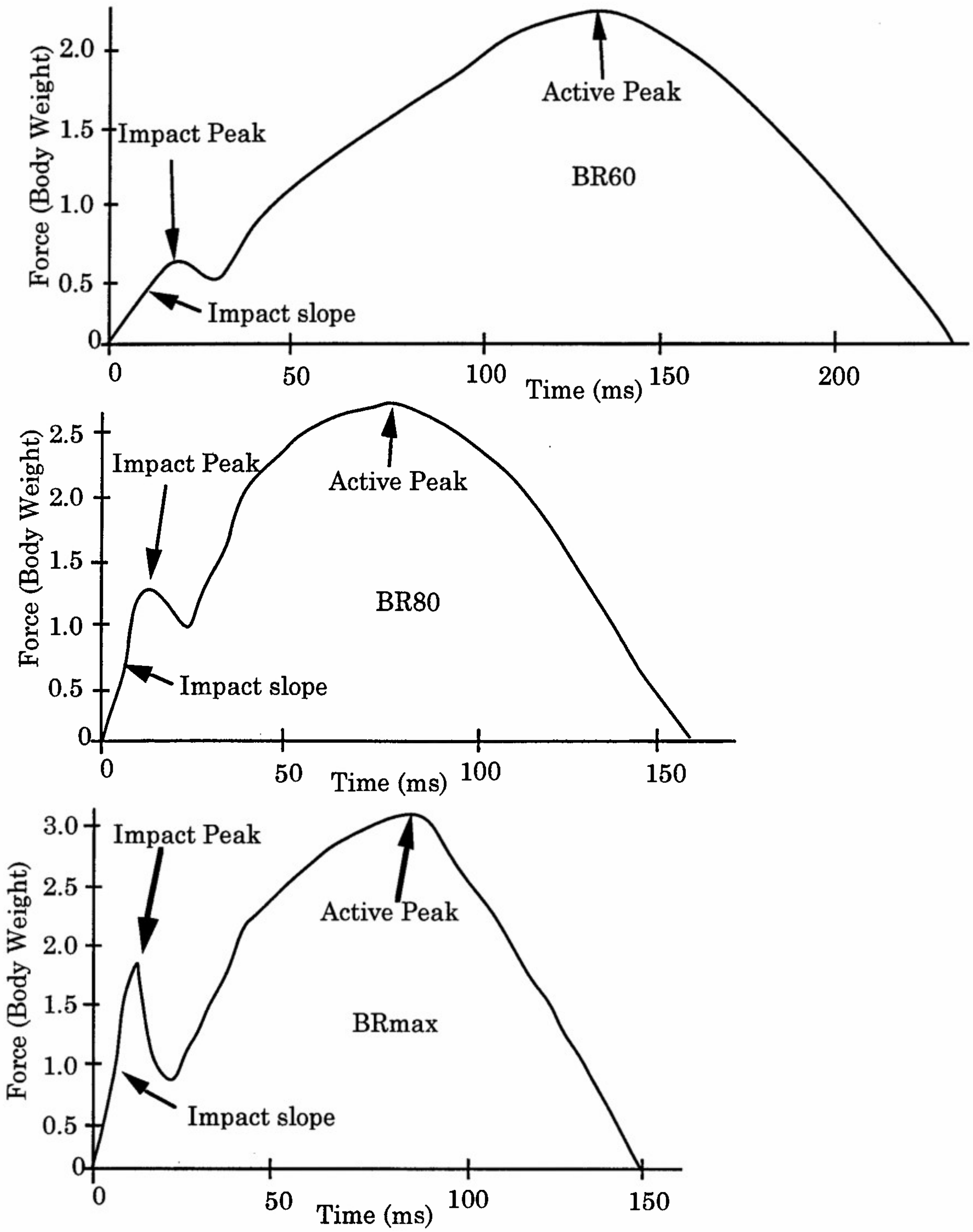

Figure 11. Representative Ground Reaction Forces (GRF) for the 3 BR Conditions.

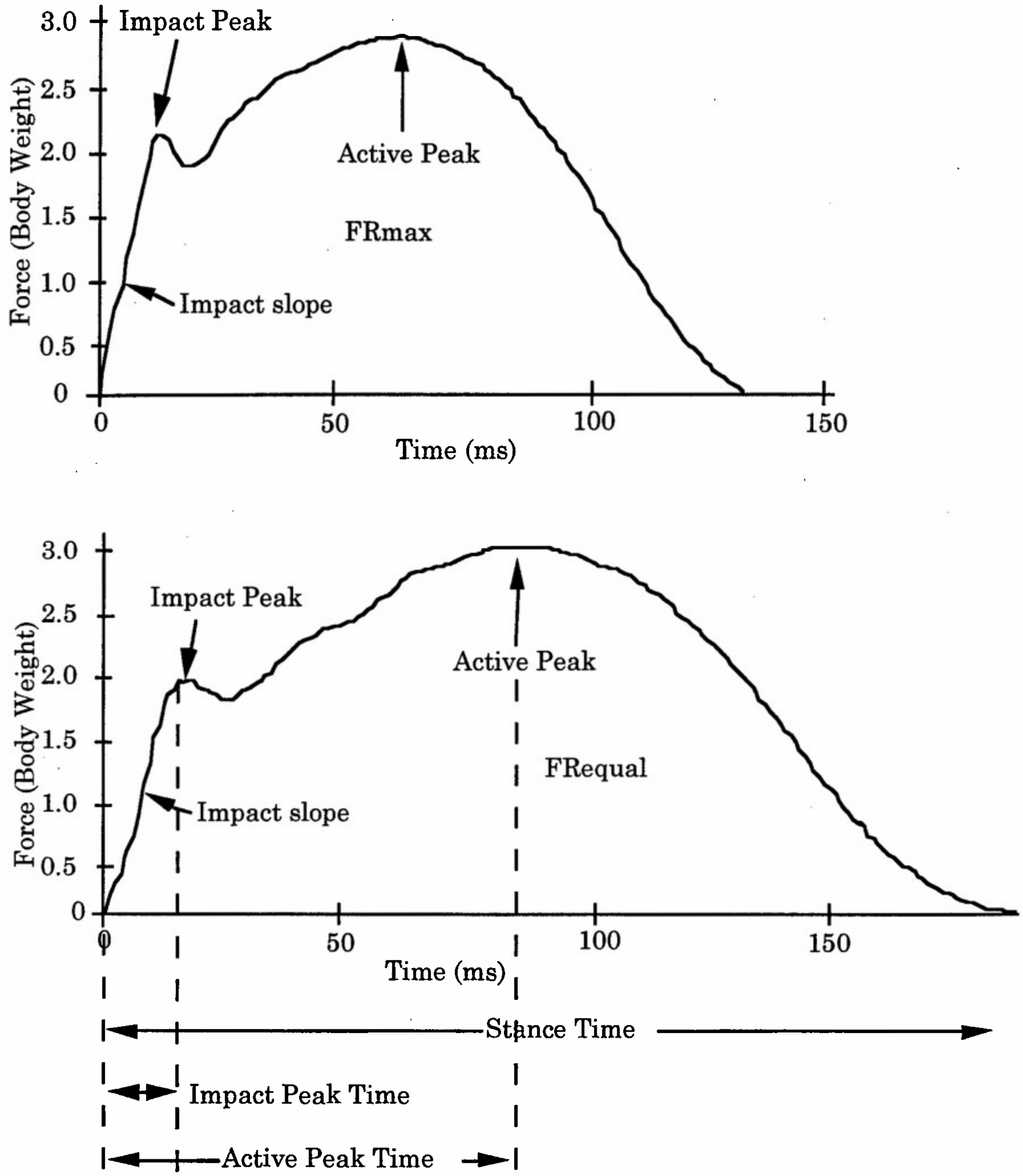

Figure 12. Representative Ground Reaction Forces (GRF) for the Two FR Conditions.

Time to Resultant Impact Peak

Time to resultant impact peak is the amount of time between ground contact and resultant impact peak. For this study, time to resultant impact peak was calculated as a percentage of stance time. Percent of stance time provided information with respect to overall timing within different conditions and thus, comparisons using percentage were conducted across conditions and groups. Table 22 includes times to resultant impact peaks as percentages of stance times for all group - conditions.

Table 22. Time to Resultant Impact Peak as a Percentage of Stance Time

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	11.12±2.53	11.64±3.37	9.05±3.91	9.86±2.32	13.15±3.79
Elite	8.80±1.50	8.54±2.51	8.51±2.73	11.49±3.39	11.86±4.49

Time to resultant impact peak as a percentage of stance time was not statistically different between the BR conditions. The Elite group had significantly earlier BR resultant impact peaks than the Athletic group, $F(1, 28) = 7.798$, $MSe = 89$, $p = 0.009$. BRmax and FRmax had no time to resultant impact peak condition or group differences. There was a significant interaction between groups and times to resultant impact peak, $F(1, 28) = 7.204$, $MSe = 58.509$, $p = 0.012$, with the Athletic group having later BRmax and earlier FRmax resultant impact peaks and the Elite group having the opposite. BRmax had significantly earlier resultant impact peaks than FRequal, $F(1, 28) = 7.104$, $MSe = 96.868$, $p = 0.013$ and the Elite group attained peak impact earlier in their stance phase than the Athletic group in the equal velocity conditions, $F(1, 28) = 6.173$, $MSe = 48.840$, $p = 0.019$.

The earlier resultant impact peaks of the Elite group for the BR conditions indicate a clear difference between the two groups. This is especially true since this variable was compared in percentage of stance time and the Elite group's stance time was shorter than the Athletic group's.

Though some differences were seen between BRmax and FRequal, it is important to note again that conditions were compared as relative of stance time and not actual time to resultant impact peak. Actual time to peak would likely have shown significantly earlier peaks for BRmax since BRmax had a shorter stance phase. Actual time is important, however, because it is associated with the loading rate on the body's tissues. The maximum impact slope (impact loading rate) is a better indicator of this factor.

Maximum Impact Loading Rate

The maximum impact loading rate (henceforth referred to as loading rate) was calculated between ground contact and resultant impact peak the highest rate over a 2 ms time period. The value represents the maximum amount of force the body must absorb as a function of time. The loading rate for all group - conditions is given in Table 23.

Table 23. Maximum Impact Loading Rate in $BW \cdot s^{-1}$

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	174.8±66.1	100.2±51.6	52.0±29.5	311.0±114	178.6±47.3
Elite	295.2±139	168.4±93.2	85.2±56.7	286.0±113	196.6±66.3

Loading rate increased significantly as BR velocity increased, $F(2, 56) = 61.35$, $MSe = 210652$, $p < 0.001$. This trend was linear, $F(1, 28) = 82.6$, $MSe = 415168$, $p < 0.001$. The Elite group had a significantly greater loading rate than the Athletic group, $F(1, 28) = 9.59$, $MSe = 122988$, $p = 0.004$. There were significant interactions in groups by condition, $F(2, 56) = 4.214$, $MSe = 14468$, $p = 0.020$ and in the linear contrast of groups by conditions, $F(1, 28) = 5.681$, $MSe = 28558$, $p = 0.024$.

FRmax had a significantly greater loading rate than BRmax, $F(1, 28) = 4.29$, $MSe = 60420$, $p = 0.048$. The groups demonstrated a tendency to differ, $F(1,28) = 3.129$, $p =0.088$, but in opposite directions, thus, there was a significant interaction between groups and conditions in the maximum velocity comparison, $F(1, 28) = 5.64$, $MSe = 79352$, $p = 0.025$. The BRmax condition had a significantly greater loading rate than the FRequal condition, $F(1, 28) = 4.26$, $MSe = 33701$, $p = 0.048$, with the Elite group showing a significantly greater loading rate than the Athletic group, $F(1, 28) = 10.23$, MSe = 71829, p = 0.003. There was a significant interaction between groups and equal velocity conditions, F(1, 28) = 4.98, MSe = 39424, p = 0.034.

The significant interaction between groups and conditions and the significant linear contrast interaction in the BR conditions were found because the Elite group's rate of increase over the three conditions was greater than the Athletic group's. Group differences as they relate to BR velocity are shown in Figure 13.

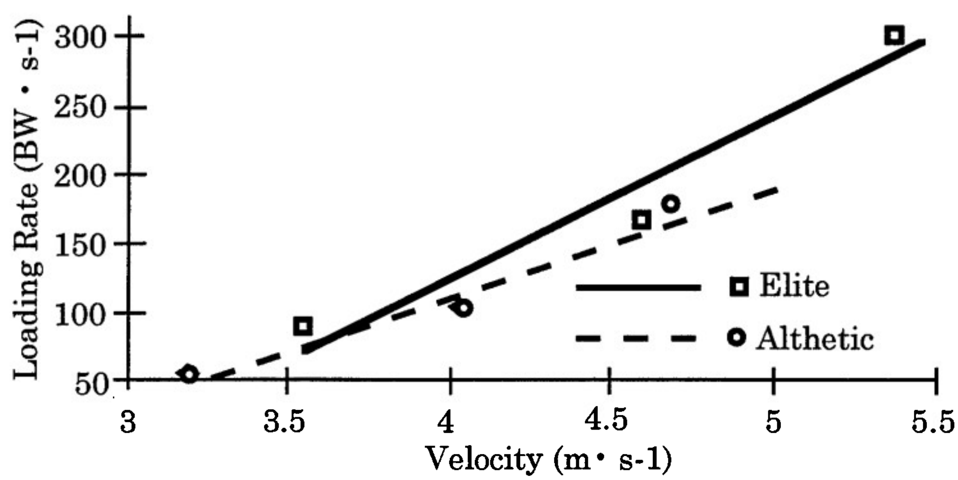

Figure 13. Athletic and Elite Group's Loading Rate by BR Velocity.

There was a significant interaction between the groups and BRmax vs. FRmax conditions, with the athletic group increasing from BRmax to FRmax, while the Elite group decreased slightly. To individually emphasize this point, every member (15) of the Athletic group had a greater loading rate in the FRmax condition (vs. BRmax), while the majority of the Elite group (8/15) had a greater loading rate during the BRmax condition (vs. FRmax).

The high rate of repetitive load that runners place on bones, tendons, ligaments and muscles has been identified as a major contributor to injuries (Nordin & Frankel, 1989). The Elite group had lower loading rates than the Athletic group during FR. The Athletic group was comprised of individuals who did a lot of FR, in general running further each week than the Elite group. Conversely, the Athletic group had a lower loading rate than the Elite group during BR. The Elite group was chosen for its practice of BR. These results suggest that as runners become proficient in BR or FR, their body's remodel as explained by Wolff's law (in Nordin & Frankel, 1989) and they have increased their loading rate. Therefore, the Athletic group had adapted to greater loading rates during FR and the Elite group had adapted to greater loading rates during BR.

Resultant Active Peak

The resultant active peak was recorded as the greatest resultant vertical and A-P force between 20-100% of stance time. Figures 11 and 12 (Resultant Impact Peak section, pages 75 and 76) show graphical examples of the ground reaction forces and the resultant active peaks for all conditions. Resultant active peaks for both groups by conditions are given in Table 24.

Table 24. Resultant Active Peak in Body Weight

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	2.63±0.37	2.53±0.33	2.27±0.22	2.73±0.26	2.72±0.20
Elite	3.00±0.46	2.81±0.36	2.43±0.36	2.90±0.30	2.94±0.34

Resultant active peaks were significantly greater as BR velocity increased, $F(2, 56) = 34.6$, $MSe = 1.69$, $p < 0.001$. This trend was linear, $F(1, 28) = 55.24$, $MSe = 3.23$, $p < 0.001$. The Elite group exhibited greater resultant active peaks than the Athletic group in the BR conditions, $F(1, 28) = 6.27$, $MSe = 1.66$, $p = 0.018$.

BRmax and FRmax resultant active peaks were statistically similar, $F(1, 28) = .001$, $p = 0.976$, $ES = 0.01$. The Elite group had greater resultant active peaks than the Athletic group in the maximum velocity conditions, $F(1, 28) = 8.82$, $MSe = 1.08$, $p = 0.006$. BRmax and FRequal resultant active peaks were also statistically similar, $F(1, 28) = 0.099$, $p = 0.755$, $ES = 0.09$. The Elite group had greater resultant active peaks than the Athletic group in the equal velocity conditions, $F(1, 28) = 12.97$, $MSe = 1.17$, $p = 0.001$.

Few researchers have conducted kinetic analyses across faster FR velocities, and thus there were few studies from which to draw BR expectations. Hamill, Bates, Knutzen, and Sawhill (1983) investigated ground reaction forces in FR at 4, 5, 6, and 7 $m \cdot s^{-1}$. They found no significant active peak changes as velocity increased. Munro, Miller and Fuglevand

(1987) studied ground reaction forces of subjects running 3.00 - 5.00 m$\cdot$s^{-1} and found an increasing active peak trend with velocity. The Munro et al. conditions were slower than this study's FR conditions and of less effort than this study's BR conditions. It is obvious that as velocity increases from zero, resultant active peak must increase. Hamill et al.'s results indicate that once a velocity of about 5 m$\cdot$s-1 is obtained, however, the active peak does not continue to increase. This study's FR data support the Hamill et al. data, as the FRmax and FRequal resultant active peak means were nearly identical. The fact that the BR resultant active peak values linearly increased with velocity while FR resultant active peaks did not, indicates the subjects used different force generation strategies to produce submaximal velocity in BR and FR. At maximum velocities, however, the subjects had similar resultant active peaks. During BR and FR maximum velocity conditions, the subjects were pushing off the ground with maximum effort. It may be that effort is a very important factor in resultant active peak for BR.

These results suggest that during BR, only at maximum velocity can the body create the active forces seen during FR. This is important for therapists who want to recreate the FR resultant active peak force generation using BR. As discussed earlier, however, BRmax also produces high resultant impact peaks and loading rates that physical therapists may want to avoid.

Time to Resultant Active Peak

The time to resultant active peak is the time between ground contact and the occurrence of the resultant active peak. Time to resultant active peak as a percentage of stance time were used to compare condition and group differences. Table 25 includes the times to resultant active peak as percentages of stance time for both groups for each condition.

Table 25. Mean Time to Resultant Active Peak as a Percentage of Stance Time

Group	BRmax	BR_{80}	BR_{60}	FRmax	FRequal
Athletic	47.64±6.05	48.57±3.95	55.71±6.90	43.96±3.41	44.07±3.57
Elite	49.96±6.77	52.12±5.90	57.83±5.32	40.97±5.16	43.08±4.39

As BR velocity increased, time to resultant active peak decreased, $F(2, 56) = 19.188$, $MSe = 536.34$, $p < 0.001$. This followed a linear trend, $F(1, 28) = 23.596$, $MSe = 953.6$, $p < 0.001$. The Athletic group demonstrated a tendency towards shorter times to resultant active peak compared to the Elite group, $F(1, 28) = 3.520$, $p = 0.071$.

FRmax had significantly shorter times to resultant active peak than BRmax, $F(1, 28) = 21.790$, $MSe = 602.173$, $p = 0.001$. There were no group differences, but there was a near significant interaction between groups and times to resultant active peak, $F(1, 28) = 3.827$, $p = 0.060$. FRequal also exhibited significantly shorter times to resultant active peak than BRmax,

$F(1, 28) = 16.29$, $MSe = 409.45$, $p < 0.001$. The Elite and Athletic groups were statistically similar in times to resultant active peak for the equal velocity conditions, $F(1, 28) = 0.205$, $P = 0.654$, $ES = 0.10$.

Munro, Miller, and Fuglevand (1987) found that active peaks occurred at between 35% and 50% of FR stance time. Cavanagh and LaFortune (1980) found FR active peaks averaged between 43% and 44% of stance time depending on whether the runner was a heel or toe striker, respectively. The FR resultant active peak time values from this study are very similar to these previously published values, even though the FRmax condition velocities were greater. The FR results from this study and those previously mentioned indicate that FR resultant active peak time is relatively constant across velocities. The BR resultant active peak times, conversely, decreased as velocity increased. Even at BRmax, resultant active peak time was not as early (as a percentage of stance time) as either of the FR resultant active peak times.

The groups differed in times to resultant active peak during the BR conditions and across BRmax to FRmax. During FRmax, the Elite group tended to reach resultant active peak sooner than the Athletic group, while during BRmax the Athletic group tended to reach resultant active peak earlier than the Elite group. These tendencies seemed to represent conflicting results. Since there was a linear trend of earlier resultant active peak times with increased BR velocity and Elite group velocity was faster than Athletic group velocity for all conditions, one would have expected the Elite group to have earlier resultant active peaks than the Athletic group. As summarized above, however, the Elite group's resultant active peaks were later in stance for the BR conditions. This later resultant active peak force generation was a clear difference between the Elite and Athletic groups.

Initial Anterior-Posterior (A-P) Peak

The initial A-P force value peak investigated was the greatest positive A-P force during the initial 10% of the stance phase. Generally, initial A-P forces in FR are negative because the foot is traveling in the direction of movement at ground contact, causing a braking force. This can be seen in Figure 14. The kinematic data showed that just prior to ground contact during BR the foot often moved in the opposite direction of movement, causing an initial propulsive force. An example of this can be seen in Figure 15. This foot movement may result from the rebounding of the thigh segment from maximum hip extension with its concomitant knee extension.

Representative examples of A-P force curves for FR and BR are shown in Figures 16 and 17 respectively. The A-P force curves dramatically differ between BR and FR during early stance. Instead of causing a braking force immediately upon impact as in FR, runners performing BR showed an initial propulsive phase at ground contact.

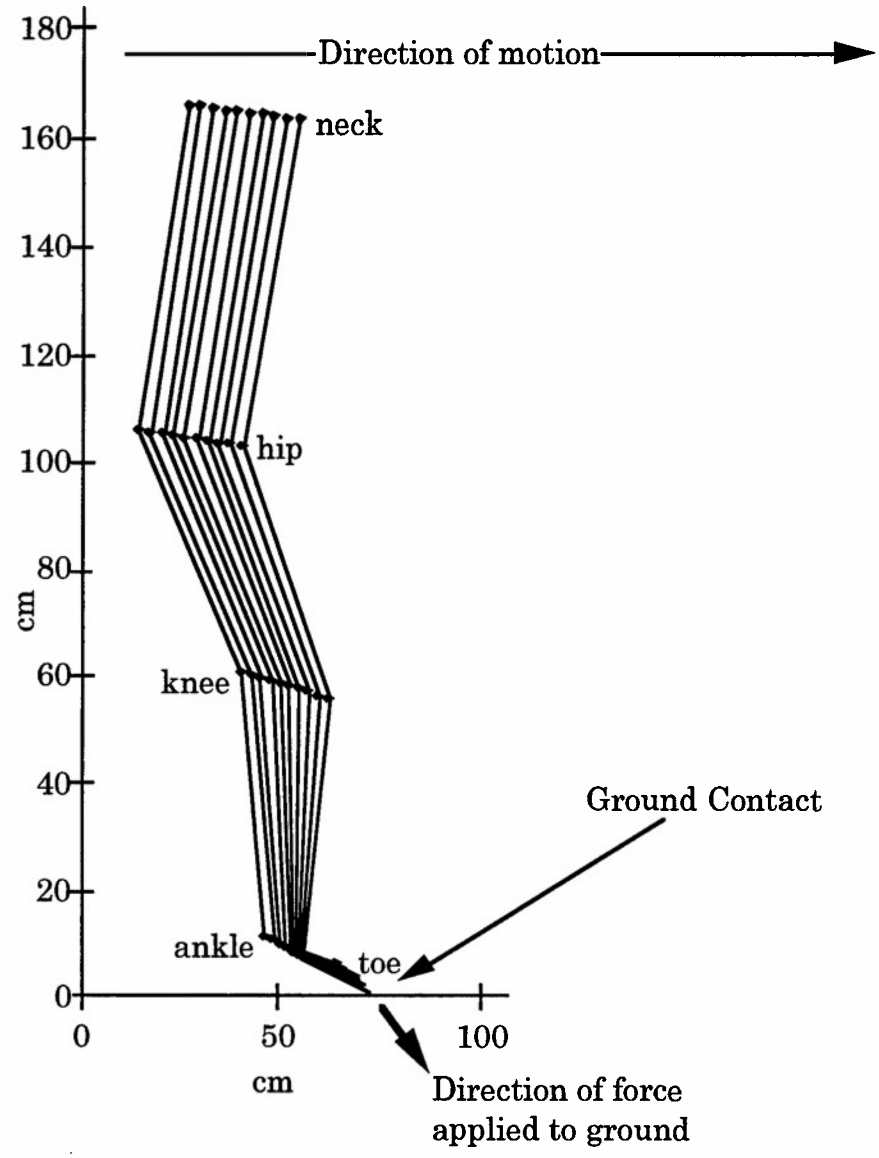

Figure 14. Kinematic Example of Subject Performing FR at Ground Contact.

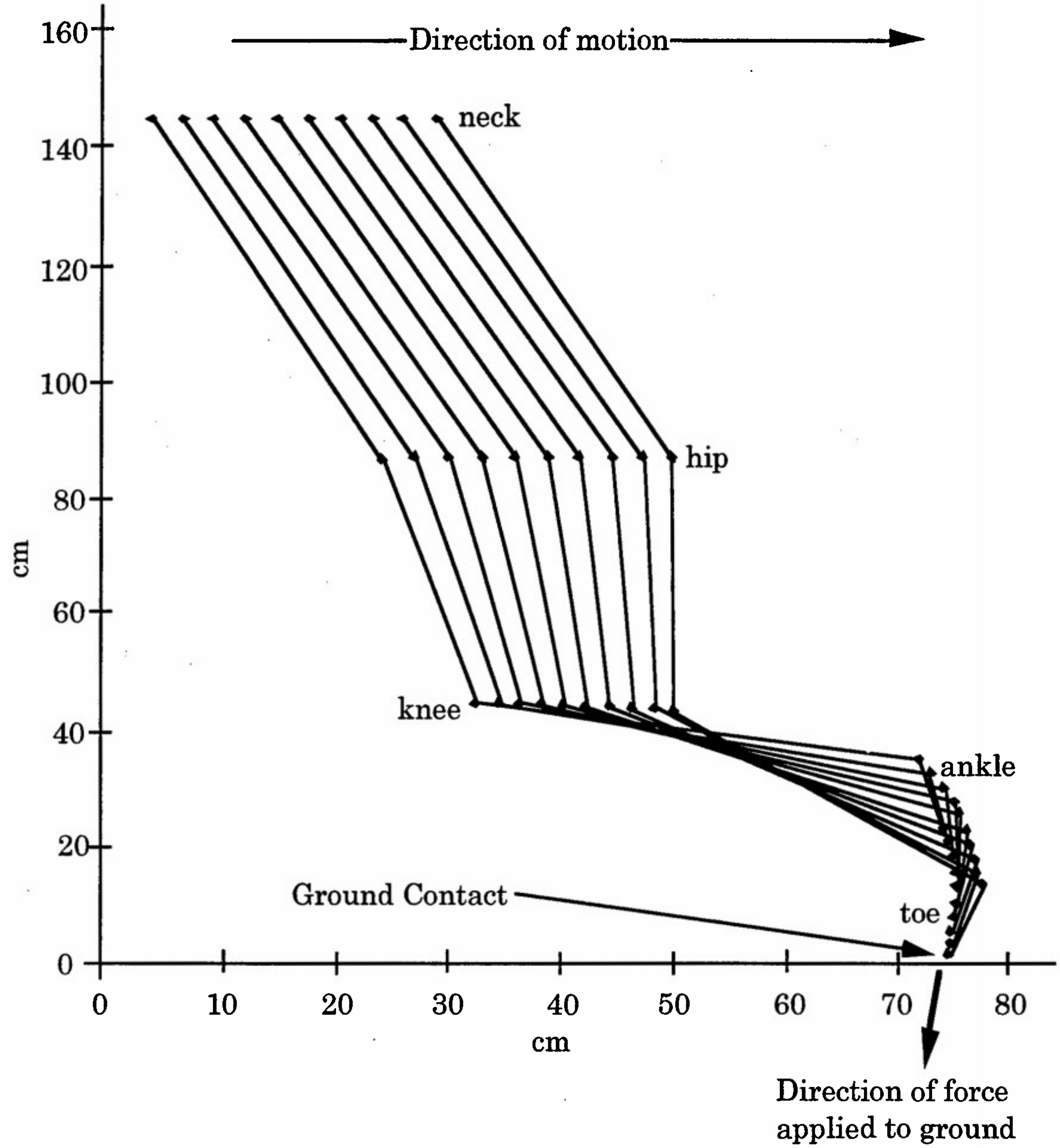

Figure 15. Kinematic Example of Subject Performing BR at Ground Contact.

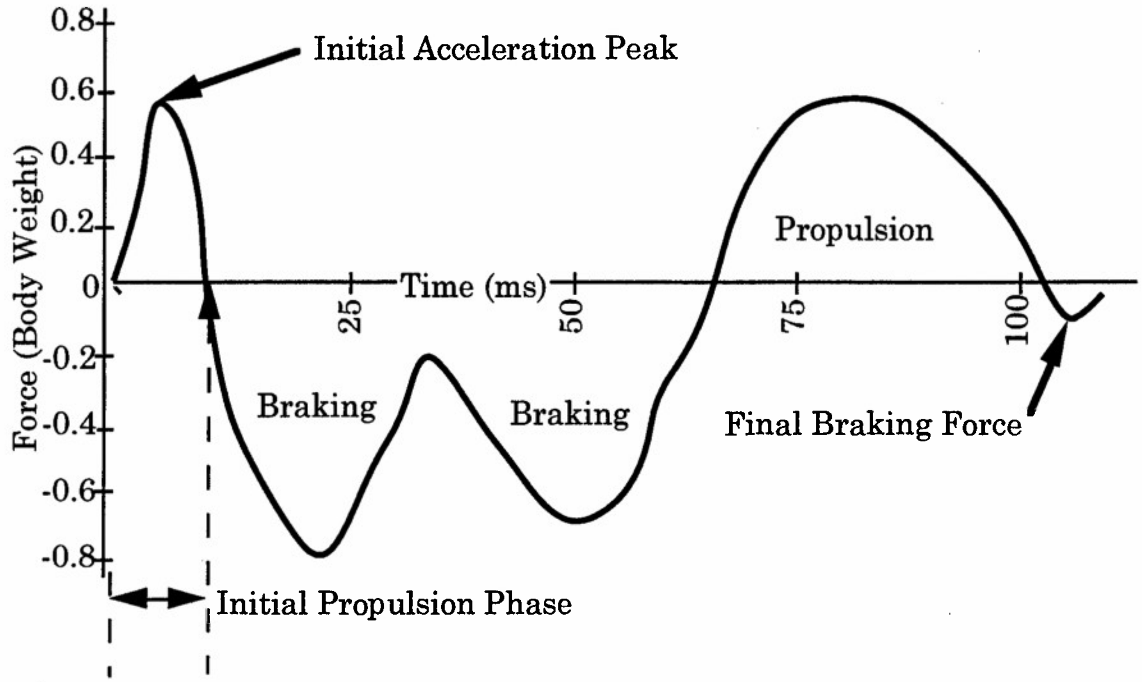

Figure 16. Representative Example of A-P Force Data from FR Subject.

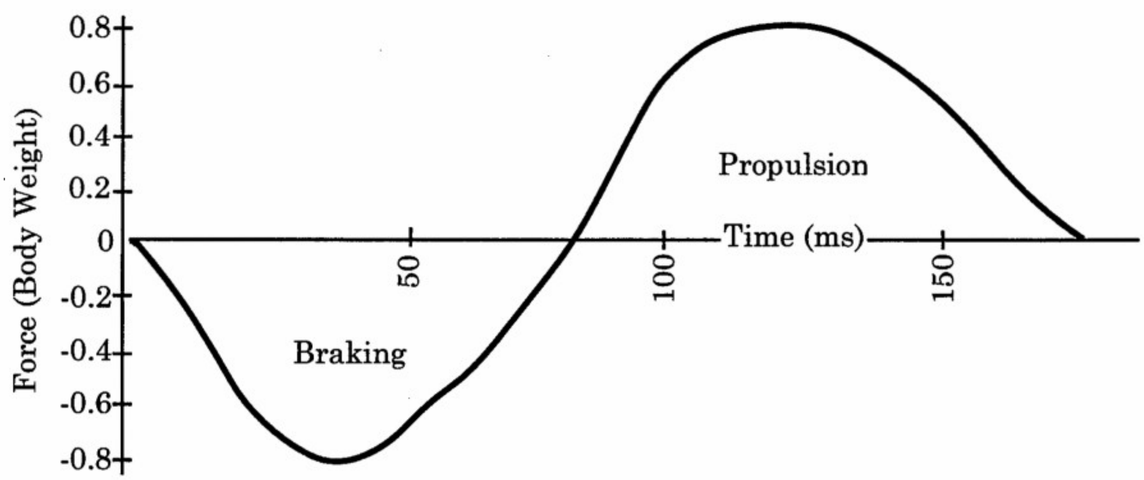

Figure 17. Representative Example of A-P Force Data from BR Subject.

Since FR at greater velocity did not display an initial positive A-P force peak, only the BR conditions were compared for this analysis. The initial A-P force peaks for both groups for the BR conditions are given in Table 26.

Table 26. Initial A-P Force Peak in Percent Body Weight

Group	BRmax	BR_{80}	BR_{60}
Athletic	21.63±15.2	13.66±10.9	10.72±10.1
Elite	45.31±20.5	26.37±18.3	21.26±22.1

Initial A-P force peaks become significantly greater as BR velocity increased, $F(2, 56) = 28.7$, $MSe = 2514$, $p < 0.001$ and followed a linear trend, $F(1, 28) = F(1, 28) = 39.39$, $MSe = 4586$, $p < 0.001$. The Elite group had significantly greater initial A-P force peak values than the Athletic group, $F(1, 28) = 8.166$, $MSe = 5505$, $p = 0.008$. There was a significant interaction between groups and conditions, $F(2, 56) = 4.25$, $MSe = 372$, $p = 0.019$, and in the linear contrast by group, $F(1, 28) = 5.56$, $MSe = 648$, $p = 0.025$.

Differences in initial A-P propulsive force in BR appeared to be an area of clear division between the two groups and could be one of the primary biomechanical reasons the Elite group was faster than the Athletic group in BR. The Elite group averaged twice the initial A-P propulsive force for all three BR conditions compared to the Athletic group. This difference was clearly marked by the two significant interactions and is illustrated in Figure 18.

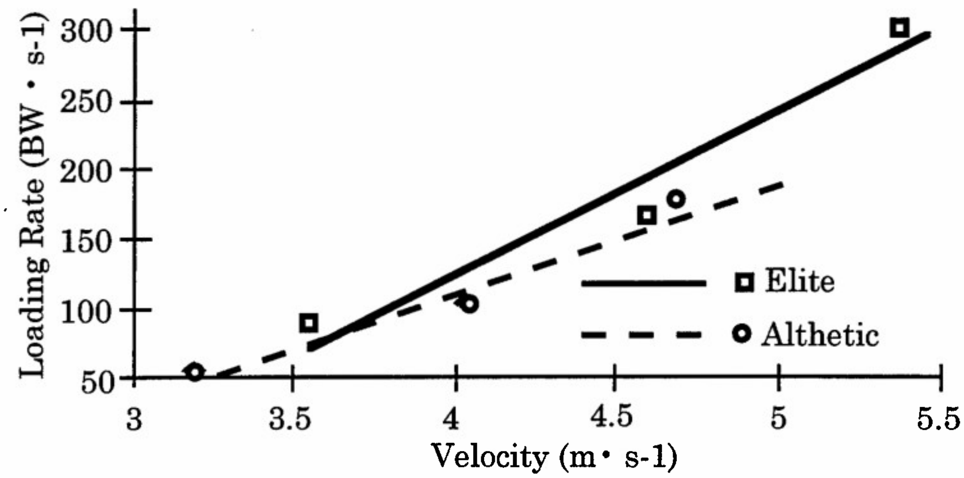

Figure 18. Initial A-P Peak of the Elite and Athletic Groups.

Anterior-posterior force generation was clearly different between FR and BR. Since an initial A-P peak is seldom seen in FR, this BR research has provided some means for its analysis. Comparing representative FR to BR A-P force curves emphasizes that FR provides the runner with one opportunity to produce a propulsive force while BR provides the runner two opportunities. However, given those two opportunities, subjects performing BRmax did not attain FRmax velocity.

Subjects in this study showed a large variability within BR initial A-P peaks. Two Athletic group subjects had no initial A-P forces during BRmax while all Elite subjects did. One of the fastest Elite subjects had an initial BRmax value of 85% of his body weight, twice the Elite average.

Final A-P Braking Force

Final A-P braking force is the force a runner exerts at toe-off which impedes his velocity. Subjects performing BR produced a braking force during the last few milliseconds of stance in the A-P plane that was not seen in FR. This difference is highlighted in Figures 16 and17 (Initial Anterior-Posterior (A-P) Peak section, page 89). A representative example of a knee to toe segment from a backward running trial is shown in Figure 19.

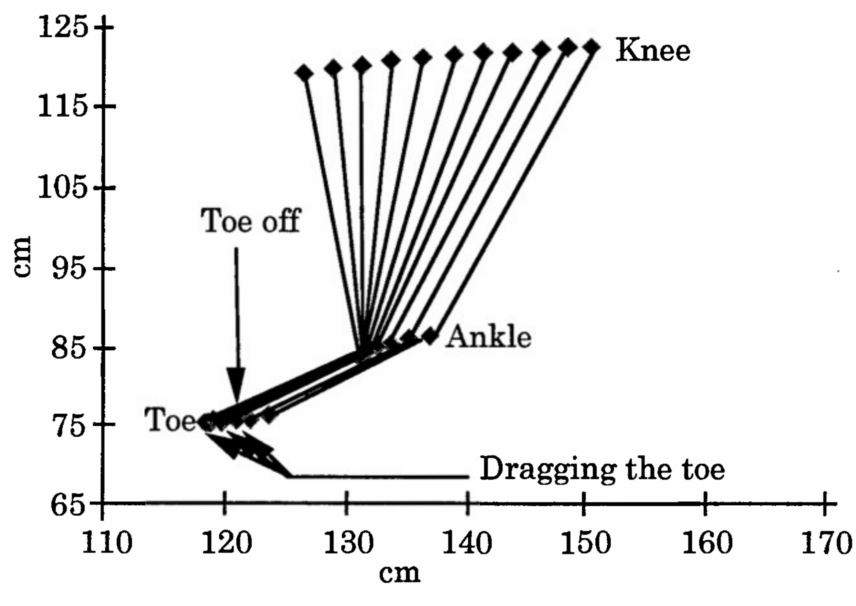

Figure 19. 50ms of BR Following Toe-Off.

Final A-P braking force was seen only in BR, so no comparisons with FR were made. Table 27 shows final A-P braking peak values as a in percent of body weight, just prior to toe-off for the BR conditions.

Table 27. Final A-P Braking Peak in Percent Body Weight

Group	BRmax	BR_{80}	BR_{60}
Athletic	-3.22±2.70	-2.48±1.76	-2.00±1.01
Elite	-2.45±1.48	-2.33±1.97	-2.17±1.68

There was a trend towards greater A-P braking forces with greater BR velocity, $F(2, 56) = 2.419$, $p = 0.098$. This trend approached significance, with greater braking at faster velocities, $F(1, 28) = 4.025$, $p = 0.055$. No group differences were seen, $F(1, 28) = 0.212$, $p = 0.649$, ES = 0.14.

This late braking force in BR was observed during preliminary testing. It appeared to be caused by friction associated with the toe of the subject's shoe dragging on the floor as the foot began to move in the forward direction (Figure 16). It was unknown, however, whether there would be differences in this force due to velocity or whether groups would differ. Results demonstrated a tendency towards increased braking force with increased velocity, which would seem to be counter productive. The group trained in BR (Elite), the faster group, did not appear to have any altered pattern towards reducing this force.

Summary

Statistical results for the BR conditions are summarized in Table 28. BR verses FR results are summarized in Table 29.

Table 28. BR Statistical Results

Category	BR conds	Linear	Group	Interaction
Velocity	BRmax ↑	BRmax ↑	E ↑	no
Foot maximum vel	BRmax ↑	BRmax ↑	E ↑	no
Stride length	BRmax ↑	BRmax ↑	E ↑	yes
Hip to toe support GC	NS	NS	NS	yes A ↑ max
Hip to toe support TO	NS	NS	E ↑	no
Stride frequency	BRmax ↑	BRmax ↑	NS	no
Stance time	BR_{60} ↑	BR_{60} ↑	A ↑	no
Trunk angle at GC	BRmax ↑	BRmax ↑	~E ↑	no
Trunk angle at TO	BRmax ↑	BRmax ↑	NS	no
Trunk angle change	BRmax ↑	BRmax ↑	S	no
Hip range of motion	BRmax ↑	~BRmax ↑	S	no
Knee range of motion	BRmax ↑	BRmax ↑	NS	no
Ankle range of motion	S	NS	NS	no
Hip angular vel at TO	BRmax ↑	BRmax ↑	NS	no
Knee angular vel at TO	NS	NS	NS	no
Ankle angular vel at TO	BRmax ↑	BRmax ↑	NS	no
Vertical oscillation	BR_{60} ↑	BR_{60} ↑	A ↑	no
Resultant impact peak	BRmax ↑	BRmax ↑	E ↑	no
Time to res. impact peak	NS	NS	A ↑	no
Maximum loading rate	BRmax ↑	BRmax ↑	E ↑	yes
Resultant active peak	BRmax ↑	BRmax ↑	E ↑	no
Time to res. active peak	BR_{60} ↑	BR_{60} ↑	E ↑	no
Initial A-P peak	BRmax ↑	BRmax ↑	E ↑	yes
Final A-P braking force	~BRmax ↑	~BRmax ↑	NS	no

~ A trend towards significance
↑ Numerical values significantly increase in the direction of BRmax or BR_{60}
S $ES \leq 0.1$
no No interaction
yes Interaction
E Elite group
A Athletic group
NS Not significant

Table 29. BR vs. FR Statistical Results

Category	BR/FR max	Group	Inter-action	BR/FR equal	Group	Inter-action
Velocity	FR ↑	E ↑	no	NS	E ↑	no
Foot maximum vel	FR ↑	E ↑	no	BR ↑	E ↑	no
Stride length	FR ↑	~E ↑	no	FR ↑	E ↑	no
Hip to toe support GC	FR ↑	A ↑	no	FR ↑	A ↑	no
Hip to toe support TO	FR ↑	NS	no	NS	NS	no
Stride frequency	BR ↑	E ↑	no	BR ↑	E ↑	no
Stance time	BR ↑	A ↑	no	BR ↑	A ↑	no
Trunk angle at GC	S	~E ↑	no	BR ↑	E ↑	no
Trunk angle at TO	NS	NS	no	S	NS	no
Trunk angle change	NS	NS	no	S	A ↑	no
Hip range of motion	FR ↑	S	no	FR ↑	NS	no
Knee range of motion	FR ↑	NS	yes	FR ↑	~E ↑	no
Ankle range of motion	FR ↑	NS	no	FR ↑	NS	no
Hip angular vel at TO	BR ↑	NS	no	–	–	–
Knee angular vel at TO	–	–	–	FR ↑	E ↑	no
Ankle angular vel at TO	FR ↑	S	no	FR ↑	S	no
Vertical oscillation	BR ↑	NS	yes	NS	A ↑	no
Resultant impact peak	FR ↑	~E ↑	no	FR ↑	NS	~yes
Time to res. impact peak	NS	NS	yes	FR ↑	A ↑	no
Maximum loading rate	FR ↑	~	yes	BR ↑	E ↑	yes
Resultant active peak	S	E ↑	no	S	E ↑	no
Time to res. active peak	BR ↑	NS	~yes	BR ↑	S	no
Initial A-P peak	–	–	–	–	–	–
Final A-P braking force	–	–	–	–	–	–

~ A trend towards significance
↑ Numerical values significantly increase in the direction of BRmax or BR_{60}
S $ES \leq 0.1$
no No interaction
yes Interaction
E Elite group
A Athletic group
NS Not significant

Nearly all the BR parameters that increased or decreased with velocity also had a significant linear trend in the same direction. Four parameters displayed no significant changes as velocity increased (knee angular velocity at toe-off, time to resultant impact peak (in percent of stance time), hip to toe support length at ground contact and hip to toe support length at toe-off). Three parameters decreased as velocity increased (stance time, vertical oscillation and time to resultant active peak). Ankle range of motion was the only parameter that remained statistically similar across all in BR velocity conditions.

The FRmax condition had greater parameter values than the BRmax condition for most of the comparisons. BRmax had greater stride frequencies, stance times, hip angular velocities at toe-off and times to resultant active peak. BRmax and FRmax were statistically similar in trunk angles at ground contact and active force peaks. There were no significant differences when comparing trunk angles at toe-off, trunk angle changes or times to resultant impact peak as a percentage of stance time.

There was not a significant difference between equal velocities of BR and FR in hip to toe support at toe-off or vertical oscillations. Furthermore, there were statistical similarities between trunk angle at toe-off, trunk angle change and resultant active peak. The other parameters were about equally divided between greater values for BR or FR.

Group comparisons across the conditions showed that the Elite group performed BR faster than the Athletic group with most parameters exhibiting significantly different values corresponding with increased BR velocity. Parameters that were not significantly different during BR group comparisons were: trunk angle at toe-off, knee range of motion, angular velocities of the hip, knee and ankle joints at toe-off and the final A-P braking force. In addition, trunk angle change and hip range of motion were statistically similar. Several of the parameter differences between the groups could have been related to the Elite group's greater velocity rather than contributors to the greater velocity. If differences in velocity are factored out of the comparisons, the following parameters appear to separate the two groups: stride length, hip to toe distance at toe-off, time to resultant impact peak, loading rate, resultant active peak, time to resultant active peak and initial A-P peak.

CHAPTER V

CONCLUSION

The purpose of the study was to quantify the kinematic and kinetic parameters associated with backward running (BR) and to compare them to: (a) BR parameters at submaximal velocities, (b) forward running (FR) parameters at maximum velocity, and (c) FR parameters at a velocity equal to BRmax (FRequal). In addition, two groups were compared. One group was comprised of individuals who used BR during athletic competition. The other consisted of individuals who habitually ran for exercise.

Summary of Procedures

Thirty male volunteers served as subjects for the study and were placed into either an Elite or Athletic group. The Elite group was comprised of 15 subjects who were members of a National Collegiate Athletic Association (NCAA) Division I university athletic team for which they performed high velocity BR as a part of competition. The Athletic group consisted of 15 university students who ran regularly. At the beginning of the testing session, each subject completed an Informed Consent Form (Appendix A) approved by the Office of Human Subjects Compliance at the University of Oregon, and a BR questionnaire (Appendix B).

Kinematic and kinetic data were obtained for each subject during five different running conditions. Kinematic data were collected using a Motion Analysis Corporation video system. Two NEC high-speed cameras with Augenieux Zoom Type 10 X 120A lenses were set up to view and record sagittal plane motion at 200Hz. The cameras were set up eight meters from the force platform, perpendicular to the path of motion so that they would each film approximately 3.5 meters of the motion with approximately 0.5 meters of overlap. Light markers were placed on the mastoid process, the greater trochanter, the lateral epicondyle of the knee, the lateral malleolus, and the lateral head of the fifth metatarsal. The marker positions were processed into planar coordinates via the Motion Analysis VP320 video-processor interfaced to a WINTEL 80486 computer system running ExpertVision™ software (Version 3.1, Motion Analysis Corporation).

Kinetic data were obtained using an AMTI force platform (Advanced Medical Technologies, Inc. Model OR6-5-1). All data were collected at 1000 Hz on separate analog channels using the Ariel Performance Analysis System (APAS). Forces were separated into vertical (Fz), anterior-posterior (Fy) and medial-lateral (Fx) components. The first channel (Fz) was also used to synchronize the force platform and video system data using a foot contact activated LCD light. The force platform was mounted flush with the hardwood floor of the laboratory at approximately the 20 meter mark of a 30 meter runway. The total kinetic sampling period was 0.5 seconds with a pre-trigger set at 10%. Three sets of Lafayette Performance timing lights (Lafayette Performance Pack, Model 63520) were used to time the subjects' velocity through the video area.

Each subject completed three BR trials at maximum velocity (BRmax), then three BR trials each at 80% and 60% of their BRmax velocity (BR_{80}, BR_{60}). Following these trials, each subject performed three FR trials at maximum velocity (FRmax) followed by three FR trials at their BRmax velocity (FRequal).

Video data were digitized using ExpertVision™ software, version 3.1. Continuous paths were generated and unwanted paths deleted using University of Oregon Biomechanics Laboratory software (Quick Basic). All data were smoothed using a fourth-order low pass Butterworth filter with a selective cut-off algorithm put forward by Jackson (1979). The cut-off frequencies were between 5 and 15 Hz. Once the marker paths were smoothed and continuous, data were placed into three investigator developed C++ programs, which combined and processed the data before calculating the specified parameters.

Three repeated measures analyses of variance (ANOVAs) were used to evaluate group and dependent variable differences. The first compared the three BR conditions, (BRmax, BR_{80}, and BR_{60}) to determine kinematic and kinetic parameter changes as BR velocity increased. The second compared the differences between the two maximum velocity conditions (BRmax and FRmax). The third compared the differences between the two equal velocity conditions (BRmax and FRequal). Level of significance was set at 0.05. In addition, effect size (ES) was used to determine whether condition or group values were statistically similar. Values being compared were considered similar if the effect size was 0.1 or less.

Summary of Results and Discussion

Most of the parameters that increased or decreased with BR velocity also had significant linear trends in the same direction. Four parameters displayed no significant changes as BR velocity increased (knee angular velocity at toe-off, time to resultant impact peak (as a percentage of stance time), hip to toe support length at ground contact and hip to toe support length at toe-off). Three parameters decreased as BR velocity increased (stance time, vertical oscillation and time to resultant active peak). Ankle range of motion was the only parameter that remained statistically similar over the increases in BR velocity.

The FRmax condition had greater parameter values than the BRmax condition for most of the comparisons. BRmax did, however, result in greater stride frequencies, stance times, hip angular velocities at toe-off and times to resultant active peak. The maximum velocity conditions were statistically similar in trunk angles at ground contact and resultant active peak forces. There were no significant differences between trunk angles at toe-off, trunk angle changes or times to resultant impact peak (as a percentage of stance time).

There were no significant differences between equal velocities of BR and FR (BRmax and FRequal) in hip to toe support at toe-off or vertical oscillations. Furthermore, there were statistical similarities between trunk angles at toe-off, trunk angle change and resultant active peaks. The other parameters were fairly evenly divided between greater values for BR or FR.

Group comparisons across the conditions showed that the Elite group performed BR faster than the Athletic group and exhibited significantly different values corresponding with increased BR velocity for most parameters. Parameters that were not significantly different during BR group comparisons included: trunk angle at toe-off, knee range of motion, angular velocities of the hip, knee and ankle joints at toe-off and final A-P braking force. In addition, trunk angle change and hip range of motion were statistically similar. Several of the parameter differences between the groups could have been related to the Elite group's greater velocity rather than contributors to that greater velocity. Factoring out velocity, the following parameters remained to separate the two groups: stride length, hip to toe distance at toe-off, time to resultant impact peak, loading rate, resultant active peak, time to resultant active peak and initial A-P peak.

Conclusion

A purpose of the study was to quantify the kinematic and kinetic parameters associated with high velocity BR as demonstrated by individuals who used it as part of a competitive sport. Specific objectives were: (a) to describe BR parameters at maximum velocity, (b) to compare BR to FR, and (c) from a clinical or coaching perspective, to determine which BR parameters appear to be the most important in order to give information to coaches regarding effective training.

As BR velocity increased from 60 to 100 percent of maximum, the velocity of the foot during the swing phase increased, stride length increased, intrinsic support length did not change, stride frequency increased, stance time decreased, trunk lean was greater during stance and trunk angle change was greater between ground contact and toe-off, there were greater hip and knee but not ankle ranges of motion (ROM), there were greater hip and ankle but not knee angular velocities at toe-off, the body's vertical oscillations decreased, resultant impact peak increased while time to resultant impact peak (as a percentage of stance time) did not change, loading rate increased, resultant active peak increased while time to resultant active peak (as a percentage of stance time) decreased, initial A-P positive peak increased, and final braking force demonstrated a tendency to increase (see Table28, page 94).

Two BR to FR comparisons were conducted, an equal effort comparison (BRmax vs. FRmax) and an equal velocity comparison (BRmax vs. FRequal). In the maximum velocity comparison, FRmax exhibited significantly greater values for 12 of the 21 parameters. BRmax demonstrated greater stride frequencies, stance times and hip angular velocities, as well as later resultant active peaks during stance phase. Resultant active peaks, times to resultant impact peak, and trunk angles were either not statistically different or were similar. In the equal velocity comparison, results were slightly different, with two additional parameters, hip to toe distance at toe-off and vertical oscillations demonstrating no significant differences.

The Elite group performed BR faster than the Athletic group, with most parameters exhibiting significantly different values corresponding with increased BR velocity. Several of the parameter differences between the groups could have been related to the Elite group's greater velocity and not contributors to that greater velocity. An illustration of this is given in Figure

20 where the two group's resultant impact peaks exhibit similar slopes and intercepts. With velocity factored out, the following parameters differed between the two groups: stride length, hip to toe distances at ground contact and toe-off, time to resultant impact peak, loading rate, resultant active peak, time to resultant active peak and initial A-P peak.

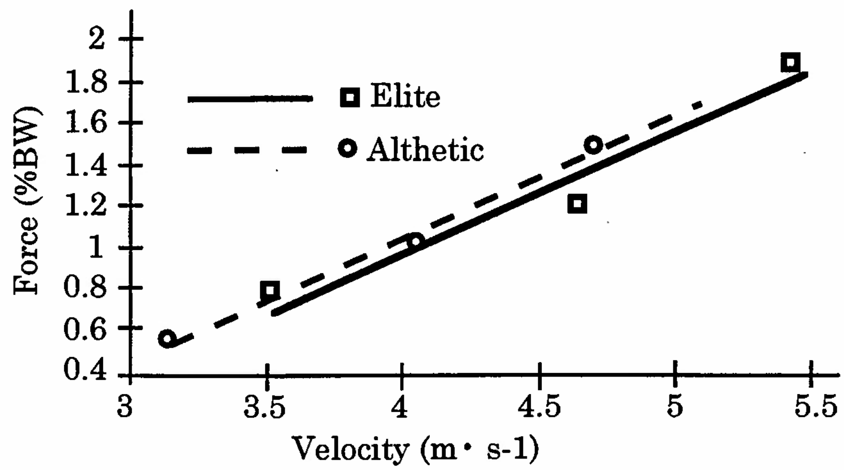

Figure 20. Resultant Impact Peaks by Velocity for the Elite and Athletic Groups.

Some of these parameters could be related to each other. The first grouping includes: resultant active peak, time to resultant active peak, and hip to toe distance at toe-off. Elite hip to toe distances at toe-off were significantly longer (Figure 21). The longer hip to toe distances could facilitate the greater resultant active peaks and longer times to resultant active peak. Hip to toe distance is the horizontal distance during which the runner's foot is in position to create a propulsive force. If this distance is greater, then there is potential for, (a) greater peak force production (as seen by the Elite group), and (b) later peak force occurrence in the stance (as seen by the Elite group). Elite group resultant active peaks were greater (indicating greater force production), and came later in the stance phase (Figure 22 & 23).

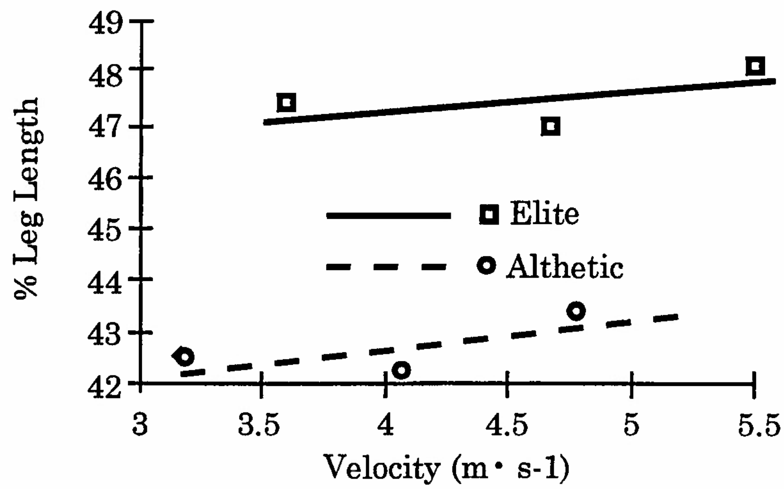

Figure 21. Hip to Toe Distances at Toe-Off for the Elite and Athletic Groups.

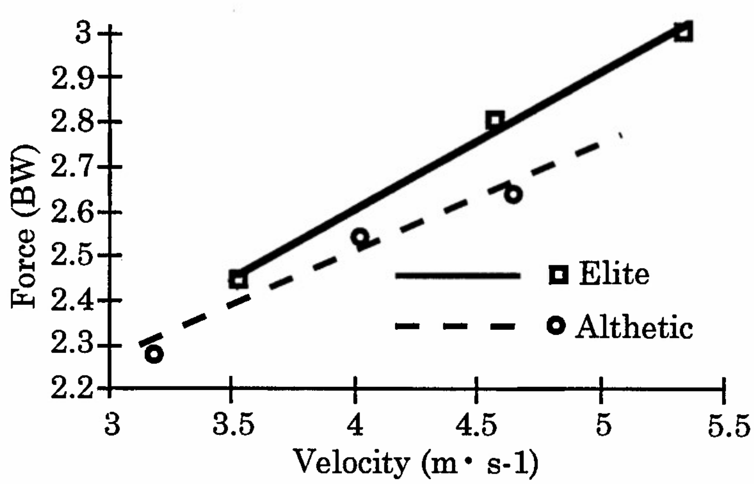

Figure 22. Resultant Active Peaks by Velocity for the Elite and Athletic Groups.

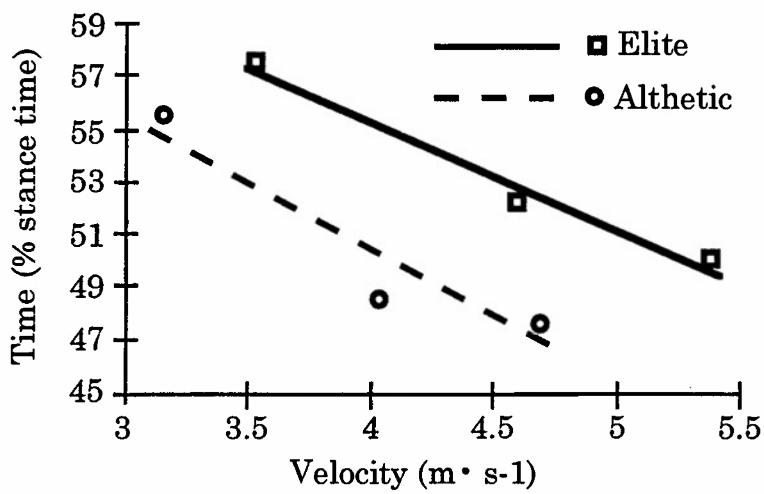

Figure 23. Times to Resultant Active Peak by Velocity for the Elite and Athletic Groups.

Hip to toe distance at ground contact, time to resultant impact peak, initial A-P peak and loading rate could also be related. Kinematically, the group differences in hip to toe distance at ground contact would have resulted in the time to resultant impact peak, initial A-P peak and loading rate differences. A greater hip to toe distance at ground contact (in front of the body's center of gravity) generally means a greater A-P braking force (though not initially in BR). The shorter hip to toe distance for the Elite group, especially in the BRmax condition, could have been a result of the foot moving opposite to the direction of movement (initiating a positive A-P force) prior to ground contact (Figure 24). A representation of this can be seen in Figure 15 (Results and Discussion, Initial A-P Peak). This foot motion (opposite of body movement) prior to ground contact is hypothesized to be the cause of the initial positive A-P peak and could have resulted from the anatomical constraint of maximum hip extension. This foot movement may result from the rebounding of the thigh segment from maximum hip extension with its concomitant knee extension. This peak was dramatically greater for the Elite group compared to the Athletic Group (Figure 25). Also, the shorter Elite hip to toe distance at ground contact compared to the Athletic group could have resulted in less time during the initial impact phase, and a shorter time to resultant impact peak. When time to resultant impact peak is shortened (Figure 26) and resultant impact peak remains the same, loading rate increases, which was observed in the Elite group (Figure 27).

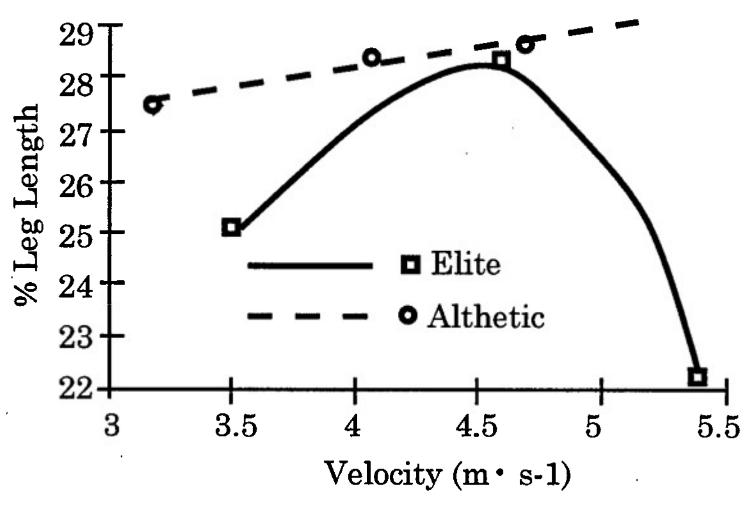

Figure 24. Hip to Toe Distances at Ground Contact for the Elite and Athletic Groups.

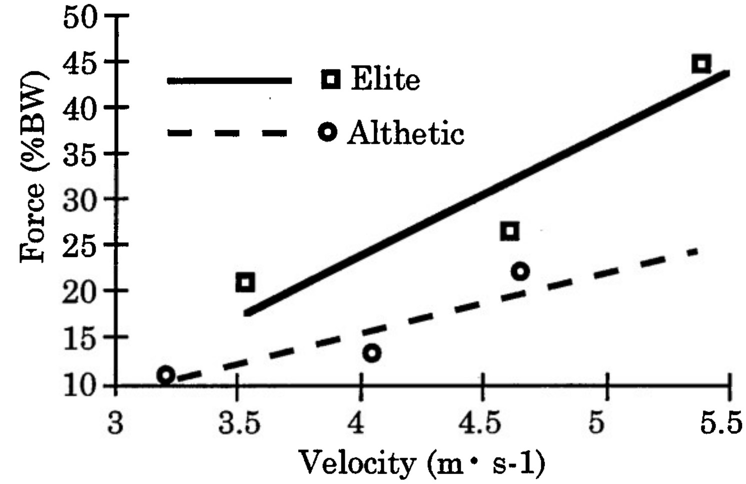

Figure 25. Initial A-P Peaks for the Elite and Athletic Groups.

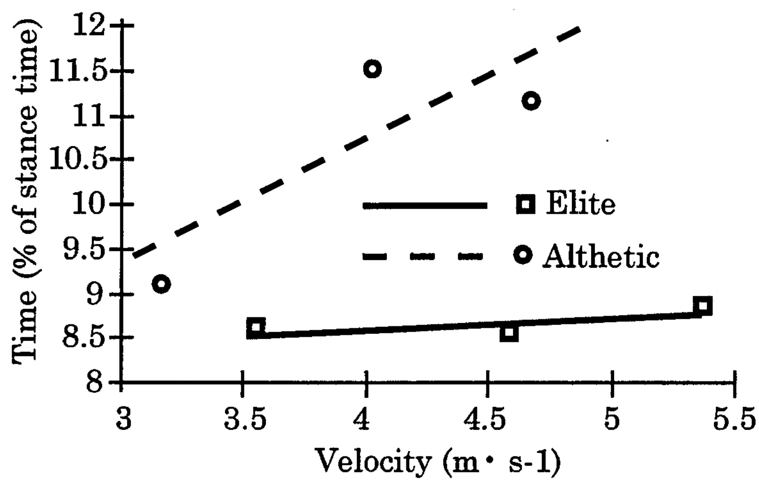

Figure 26. Times to Resultant Impact Peak for the Elite and Athletic Groups.

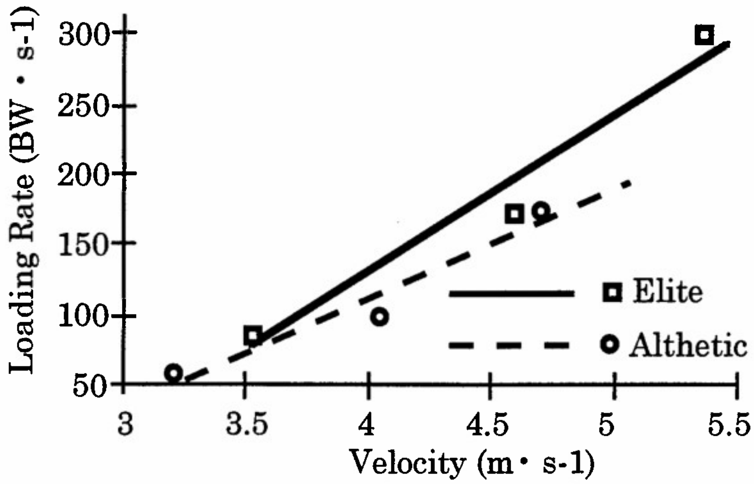

Figure 27. Loading Rates for the Elite and Athletic Groups.

Stride length is the remaining parameter that separated the two groups once velocity was factored out. The Elite group's stride length did not change between BR_{80} and BRmax (Figure 28). This leveling off is similar to reported results for FR of sprinters (Mero, Komi & Gregor, 1992). To achieve a true maximum velocity, a runner has an optimum stride length to stride frequency ratio. Only one combination of the two can produce maximum velocity at any one given instant in time. As velocity decreases, however, a runner can manipulate his stride length and/or frequency to achieve the desired speed. During BR_{80}, the Elite group might have chosen to maximize stride length, but if this was their choice, it was a group choice. It could also have been an effect of their sports training.

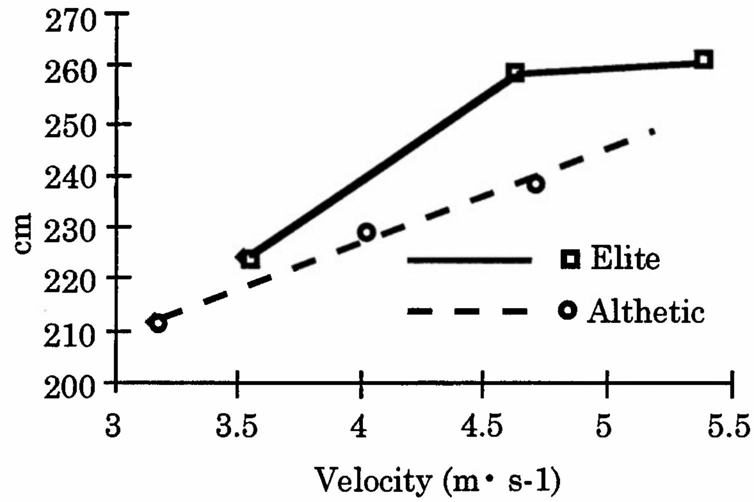

Figure 28. Stride Lengths for the Elite and Athletic Groups.

The Elite group subjects were expected to be faster at BR because they used it in their sport. It was hypothesized that the Elite group would show a BR training effect, superior natural BR ability, or both. While the Elite group was clearly faster at BR than the Athletic group, they were clearly faster at FR as well, and the percentage difference of maximum BR to FR velocity was only one percent between the groups. This could suggest that to get faster at BR, one should get faster at FR or, simply, that faster forward runners are faster backward runners. Looking at the population data, this conclusion appears sound. However, the more homogeneous the group, such as the Elite group, the less likely a correlation will exist. The correlation of the 30 subject's maximum BR to FR velocities did not explain a significant portion of the variance (Velocity in Results and Discussion, page 44). Thus, it is more than FR speed that makes one fast at BR.

The Elite group in this study used BR during athletic competition, but it was unclear how much BR they actually practiced. The majority of the Elite subjects were football players who practiced multi-directional movement drills, but not a lot of pure BR drills, or BR drills especially for speed. The fastest Elite subject recorded a velocity about 2 $m \cdot s^{-1}$ slower than the average pace of the World Record 100 yard backward run. This difference in velocities could have been due to the short length of the runway as mentioned in the Limitations section of Chapter I. However, several subjects did experiment with shortening their runway length during the BRmax conditions. These changes of between three and five meters did not seem to influence their overall velocity, which could indicate subjects were at maximum BR velocity prior to the data collection area.

If an athlete could run backwards at greater than 7.5 $m \cdot s^{-1}$, they would be able to "cover" their opponent while running backwards for up to 20 meters (about 3 seconds), which is a long time in some sports. Perhaps these findings, along with others to follow will give coaches and athletes greater knowledge of BR so that greater velocities can be achieved.

In conclusion, coaches and athletes should understand three findings from this study. First, though specific kinematic and kinetic parameters were identified which separated the Elite from the Athletic group, more study is needed to determine how an athlete could improve these parameters. Second, if an athlete is already fast at FR, then they are not likely to improve their BR speed with FR training alone. BR training may increase BR speed through specific muscular development beneficial to BR velocity and enhance BR balance and timing. Finally, increasing stride length could be the one understandable concept for a coach to pass on to athletes. An athlete's attempt to increase BR stride length by increasing leg drive or propulsion could promote greater levels of the other kinematic and kinetic parameters such as initial A-P peak, resultant active force, and intrinsic support length, that separated the two groups in this study.

Recommendations for Future Studies

1. Replicate part or all of this study to provide measures of reliability and validity.

2. Evaluate joint moments of the hip, knee and ankle joints to determine their role as BR velocity increases.

3. Compare kinematic and kinetic parameters of a group pre and post BR training.

4. Conduct a kinematic analysis of athletes during competitive contests to determine effects of the task (having to use BR to cover a runner).

5. Replicate this study using female athletes and controls to provide information as to whether the trends found are gender specific.

6. Determine the preferred transition speed (PTS) for backward walking to BR.

7. Determine muscle activation patterns and levels for normal BR.

8. Determine the age that a child develops the ability to perform BR.

APPENDIX A

INFORMED CONCENT FORM

INFORMED CONSENT

QUANTIFICATION OF KINEMATIC AND KINETIC HIGH SPEED BACKWARD RUNNING PARAMETERS

You are invited to participate in a study being conducted by Alan Arata, a doctoral student at the University of Oregon in the Department of Exercise and Movement Science. The purpose of this study is to investigate the parameters associated with different speeds of backward running with hopes of identifying key elements to improve backward running speed. The results will contribute to the completion of Alan Arata's doctoral dissertation and a better understanding of backward locomotion as it is used in sports, physical therapy and balance control.

The experiment will be held in the Biomechanics Lab of the University of Oregon. In this experiment, you will be asked to perform multiple backward and forward running trials at various percentages of your maximum speed. Small reflective markers will be placed over some of your joints. Also, electrodes for recording muscle activity will be placed on your skin's surface. You will be asked to wear shorts and a sleeveless shirt so that the markers will be in the camera's view.

Testing will be conducted over a maximum of two days, no longer than two hours of your time per test. You will run backwards and forward at various speeds in front of a video camera and over a force platform. There will also be a short questionnaire to fill out.

To reduce the risk of possible skin irritation, hypoallergenic gel and tape will be used. Incidence of skin response to the tape or gel is low or non-existent. Also, you may get tired or uncomfortable during some of the tasks. To minimize this, testing can be paused or stopped at your request.

So that you remain anonymous in our files, all data will be coded with letters and numbers and kept locked in the primary investigator's (PI's) office. All data and videos will be destroyed five years after the completion of the project. Your name will not appear in the investigator's files. Coding is done to keep subject names anonymous. Information obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. We may wish to use the video data of your movements for educational purposes in the future. But even if you agree to this, your identity will not be disclosed as the video system only records position coordinates of each reflective marker. If you would like to give your permission for use of the video recording for educational purposes (such as classes or conferences), please place your initials by "yes" below. If you do not wish to give permission at this time, please initial by "no". Video data will not be used commercially.

yes ____________________ no ____________________

As your permission is voluntary, your decision will not affect your relationship with the Biomechanics Lab. If you decided to participate, you are free to withdraw your consent and discontinue participation at any time without penalty.

You or your own insurer are responsible for any medical expenses resulting from injuries to you caused by your participation in this research project. If you are a UO student or employee covered by a UO medical plan, the terms of that plan may apply to any such injuries. Should you suffer injury as a result of participating in this project, you would be free to file a claim against the State of Oregon pursuant to ORS 30.260-.275. Questions regarding claims should be directed to the Assistant to the President for Legal Affairs (541)346-3843, University of Oregon, Eugene, Oregon 97403. Any such incidents should also be reported to the Committee for the Protection of Human Subjects (541)346-2510 at the same address. If the Project or the University were to be legally at fault and liable, the largest possible recovery would be $200,000 to any claimant and $500,000 to all claimants for any single incident.

If you have any questions, please feel free to contact Alan Arata at (541) 346-1033 and his faculty advisor Dr. Bates at (541) 346-1040. If you have questions regarding your rights as a research subject, contact Human Subjects Compliance, University of Oregon, Eugene, OR 97403, (541) 346-2510. You will be given a copy of this form to keep.

Your signature indicates that you have read and understand the information provided above, that you willingly agree to participate, that you may withdraw your consent at any time and discontinue participation without penalty, that you will receive a copy of this form, and that you are not waiving any legal claims, rights or remedies.

Participant Signature ______________________________ Date ___________

Witness Signature ________________________________ Date ___________

Primary Investigator Signature ______________________ Date ___________

APPENDIX B

SUBJECT QUESTIONAIRE AND WORKSHEET

Subject # _______ Worksheet

Name: ______________________ Today's Date: __________
DOB: ____/____/____ Height:__________ Weight: ____________
In what sport activities are you currently involved?

____

How long have you been competing/involved in your sport?

____

What position do you play in your sport?

____

How much time per week do you working out? _____ running? ______

Do you have any injuries that might affect your performance during this study? _________

____

BRmax Time _________ 10 m BR time ________ 10 m FR time _________

80% high ________ 80% low ________ 60% high ________ 60% low ________

FRequal high__________ FRequal low _________

Cond/Trial	*Time*	*Name given*	*Other comment*
C1T1			
C1T2			
C1C3			
C2T1			
C2T2			
C2T3			
C3T1			
C3T2			
C3T3			
C4T1			
C4T2			
C4T3			
C5T1			
C5T2			
C5T3			

APPENDIX C

SUBJECT INFORMATION

Table 30. Athletic Group Subject Information

Subject #	Group	Age (years)	Height (cm)	Weight (kg)
1	A	21.51	181	63.18
2	A	28.03	179	93.64
3	A	27.02	170	74.55
4	A	23.53	180	81.36
5	A	20.93	177	69.55
6	A	18.52	184	66.36
7	A	21.72	171	66.36
8	A	22.43	182	84.09
9	A	21.67	196	76.82
10	A	21.58	187	85.91
11	A	21.77	186	80.45
12	A	21.03	181	70.23
13	A	21.70	177	81.82
14	A	18.67	188	82.27
15	A	19.07	186	79.09
	MEAN	21.94	182	77.05
	SD	2.65	6.66	8.52

Table 31. Elite Group Subject Information

Subject #	Group	Age (years)	Height (cm)	Weight (kg)
21	E	22.73	191	94.09
22	E	21.48	179	92.73
23	E	22.98	192	101.14
24	E	20.58	186	95.91
25	E	21.25	195	97.27
26	E	19.13	186	86.36
27	E	19.73	189	90.45
28	E	19.27	173	81.36
29	E	23.42	182	83.18
30	E	19.40	185	90.91
31	E	21.21	191	79.32
32	E	19.68	173	75.91
33	E	20.62	174	69.55
34	E	21.90	185	87.27
35	E	20.33	180	84.09
	MEAN	20.91	184	87.30
	SD	1.39	7.06	8.60

APPENDIX D

COMPUTER PROGRAMS WRITTEN FOR THIS DISSERTATION

Combine.cpp
Kinetics.cpp
Kinematics.cpp

```
//***********************************************************************
//
//                                                    Combine.cpp
// Alan W. Arata,                                     4 Nov 98
//
//***********************************************************************
// This program takes data from two side by side Motion Analysis cameras
// and merges the two data sets into one. This program uses 5 body
// markers and one sync light. The sync light is not seen by the second
// camera and the sync light is the last marker. This data is set up as
// global variables below. Output will appear as follows.

// 2, 38, 115
// 10.2, 207.8, 9.7, 149.7, 8.4, 123.4, 9.8, 84.6, 10.9, 81.1

// 2 is sync on, 38 is sycn off, 115 is ipsolateral ground contact
//xNeck, yNeck, xHip, yHip, xKnee, yKnee, xAnkle, yAnkle, xToe, yToe


#include <iostream.h>
#include <fstream.h>          // for file i/o redirection
#include <stdlib.h>           // for exit
#include <iomanip.h>          // for set precision
#include <string.h>           // for string copy

const int NUMPOINTS = 5;       // five marks and force plate sync light
const int NUMCAMERAS = 2;      // number of cameras to be merged
const int NUMTRIALS = 3;       // number of trials
const int SYNCMARKER = 6;      // marker # of sync given by Motion Analysis
const int TOEMARKER = 5;       // toe marker number

const float FRAMERATE = 200.0;  // frame rate in Hz float
const float SAMPLETIME = 1.0;   // frame rate in Hz

void intoString(char[], int, int);
void openfiles(char[], char[], float[][NUMCAMERAS*NUMPOINTS], int);
void findSync(char[], int&, int&);
void  joinPaths(float[][NUMCAMERAS*NUMPOINTS]);
void printArray(char[], char[], float[][NUMCAMERAS*NUMPOINTS], int,
int);
```

```
int footDown(float[][NUMCAMERAS*NUMPOINTS], int);

void main()
{
float  mergedData[205][NUMCAMERAS*NUMPOINTS];

int subjectStart,           // first subject data to be processed
    subjectEnd,             // last subject data to be processed
    conditionStart,         // first condition number to be processed
    conditionEnd,           // last condition number to be processed
    syncOn,                 // array index when sync light is on
    syncOff;                // array index when sync light is off

char filename1[20];         // Max. 20 characters plus '\0'
char filename2[20];         // Max. 20 characters plus '\0'
char abort;                 // Allows user to quit program

cout << "This program assumes the files are listed in the format of" << endl;
cout << "S1C1T1.KN?.  The KN1 files are the first camera & the " << endl;
cout << " KN2 files are the second camera." << endl << endl;
cout <<"What subject number do you want to start with?" << endl;
cin >> subjectStart;

cout <<"What subject number do you want to end with?" << endl;
cin >> subjectEnd;

cout <<"What condition number do you want to start with?" << endl;
cin >> conditionStart;

cout <<"What condition number do you want to end with?" << endl;
cin >> conditionEnd;

cout << "The trials will automatically be between 1 and " << NUMTRIALS <<
endl;

cout << "If any of the parameters are incorrect, enter q otherwise press r and
return" << endl;

cin >> abort;
```

```
while (abort != 'q' && abort != 'Q')    // allows user to quit program if they don't
                                        // like the parameters they have inputed
  {
  for (int i = subjectStart; i <= subjectEnd; i++)  // loops place the file
    {                                               // name in a string format
    int n = 0;
    filename1[n] = 'S';
    n++;
    intoString(filename1, n, i);
    n++;
    if (i > 9)
      n++;

    filename1[n] = 'C';
    n++;
              // loop places condition number in string
    for (int j = conditionStart; j <= conditionEnd; j++)

      {
      intoString(filename1, n, j);
      n++;
      if (j > 9)
        n++;

      filename1[n] = 'T';
      n++;
                // loop places trial number in string
                // and call the functions
      for (int k = 1; k <= NUMTRIALS; k++)
        {
        intoString(filename1, n, k);
        n++;
        if (k > 9)
          n++;

        filename1[n] = '.';
        n++;
        filename1[n] = 'K';
        n++;
        filename1[n] = 'N';
        n++;
```

```
            filename1[n] = '1';
            n++;
            filename1[n] = '\0';
            strcpy(filename2, filename1); // copies filename with KN1
            filename2[n-1] = '2';            // changes filename to KN2

            findSync(filename1, syncOn, syncOff);
            openfiles(filename1, filename2, mergedData, syncOn);
            joinPaths(mergedData);
            printArray(filename1, filename2, mergedData, syncOn, syncOff);

            n = n-5;
            } // end of for k
        n = n-2;

        } // end of for j

    } // end of for i statement
    abort = 'q'; // ends loop
  } // end of while
} // end of main

//**********************************************************************
// This function finds the time when the sync light comes on and off -- or the
// beginning and end of the first ground contact - sync'ed with the force plate

void findSync(char filename1[],
            int& syncOn,
            int& syncOff)
{
ifstream ifs;

int markerNum,              // input marker number
  frameNum;                 // input frame number

int found = 0;
int counter = 1;

float xValue,
     yValue;
```

```
ifs.open(filename1);        // open the output file stream

if (ifs.fail())             // check for success
    {
    cout << "Error opening output file stream -- existing." << endl;
    exit (1);
    }

ifs >> markerNum >> frameNum >> xValue >> yValue;

                // while loop eats data until Sync marker is found
while (markerNum != SYNCMARKER  && ifs)
    ifs >> markerNum >> frameNum >> xValue >> yValue;

while (found != 2 && ifs)  // this loop finds first and last sync marker locations
    {
    if (found != 1 && xValue > 1.0)
        {
        found = 1;
        syncOn=counter;
        }
    if (found ==1 && xValue < 1.0)
        {
        found = 2;
        syncOff=counter - 1;
        }
    ifs >> markerNum >> frameNum >> xValue >> yValue;
    counter++;
    } // end while

ifs.close();

} // end findSync function

//**********************************************************************
// This function retrieves an existing data base from a path edited file
// and combines them into one array.

void openfiles(char filename1[],
            char filename2[],
            float mergedData[][NUMCAMERAS*NUMPOINTS],
```

```
            int syncOn)
{
ifstream ifs;

int markerNum,          // input marker number
    markerCounter,      // a marker counter to help exit a loop
    frameNum;           // input frame number
int MMCounter;          // multiple marker counter - found on both cameras
int loopexit = 0;       // loop breaker

float xValue,
     yValue,
     xScale,
     yScale;

ifs.open(filename1);    // open the output file stream

if (ifs.fail())         // check for success
   {
   cout << "Error opening output file stream -- existing." << endl;
   exit (1);
   }

for (int f = 0; f < NUMPOINTS*2; f++) // initiates mergedData array to zero
   for (int d = 0; d < int(FRAMERATE*SAMPLETIME); d++)
      mergedData[d][f] = 0.0;

ifs >> markerNum >> frameNum >> xValue >> yValue;

while (ifs && markerNum < SYNCMARKER)    // inputs KN1 file into the
array
   {
   if (frameNum > syncOn - 3 && frameNum <= syncOn +
int(FRAMERATE*SAMPLETIME))
      {
      mergedData[frameNum+2-syncOn][(markerNum-1)*2] = xValue;
      mergedData[frameNum+2-syncOn][(markerNum-1)*2+1] = yValue;
      }
   ifs >> markerNum >> frameNum >> xValue >> yValue;
   }
```

```
ifs.close();

//****************** closing KN1 opening KN2 ************************

ifs.open(filename2);    // open the output file stream

if (ifs.fail())         // check for success
    {
    cout << "Error opening output file stream -- existing." << endl;
    exit (1);
    }

cout << filename2 << " being merged with " << filename1 << endl;

ifs >> markerNum >> frameNum >> xValue >> yValue;

                    // loop runs while data present
while (ifs && markerNum < SYNCMARKER && loopexit == 0)
    {
    MMCounter = 0;
    markerCounter = markerNum;

            // Loop runs for each marker #.  Embedded if statments determine
            // the conversion factor and which array data is present in.
    while (ifs && markerCounter == markerNum && frameNum <= syncOn +
        int(FRAMERATE*SAMPLETIME))
        {
        if (MMCounter != 0 && mergedData[frameNum+2-syncOn]
            [(markerNum-1)*2] > 0.5 && xValue > 0.5)
            {
            xScale = (xScale + (mergedData[frameNum+2-syncOn]
                [(markerNum-1)*2] -  xValue))/2;
            yScale = (yScale + (mergedData[frameNum+2-syncOn]
                [(markerNum-1)*2+1] - yValue))/2;

            mergedData[frameNum+2-syncOn][(markerNum-1)*2] = (xValue
                +xScale)*MMCounter/100  + mergedData[frameNum+2syncOn]
                [(markerNum-1)*2]*(100-MMCounter)/100;
            mergedData[frameNum+2-syncOn][(markerNum-1)*2+1] = (yValue
                + yScale)* MMCounter/100 + mergedData[frameNum+2-
                syncOn][(markerNum-1)*2+1]*(100- MMCounter)/100;
```

```
        if (MMCounter < 98)
            {
            MMCounter = MMCounter+3;
            }
        }

    if (mergedData[frameNum+2-syncOn][(markerNum-1)*2] < 0.5 &&
        xValue > 0.5)
        {
        mergedData[frameNum+2-syncOn][(markerNum-1)*2] = xValue +
        xScale;
        mergedData[frameNum+2-syncOn][(markerNum-1)*2+1] = yValue
        + yScale;

        if (markerNum == 1 && MMCounter == 0)
        cout << "WARNING, neck marker data invalid!" << endl;
        }

    if (MMCounter == 0 && mergedData[frameNum+1-syncOn]
        [(markerNum-1)*2] > 0.5 && xValue > 0.5)
        {
        xScale = mergedData[frameNum+2-syncOn][(markerNum-1)*2] -
        xValue;
        yScale = mergedData[frameNum+2-syncOn][(markerNum-1)*2+1] -
        yValue;
        MMCounter = MMCounter+3;

        }

    ifs >> markerNum >> frameNum >> xValue >> yValue;

    } // while ifs loop

while (ifs && frameNum != 1) // eats unneeded lines
    ifs >> markerNum >> frameNum >> xValue >> yValue;

    if (markerNum == TOEMARKER && frameNum > syncOn +
    FRAMERATE* SAMPLETIME)
        loopexit = 1;  // breaks out of the loop
```

```
    } // while markerNum loop

ifs.close();

} // end function

//***********************************************************************
// This function prints the array of the combined data from two cameras. The
// array is printed with the same name as its parent files but with the
// extension KN3.

void printArray(char filename1[],
                char filename2[],
                float  mergedData[][NUMPOINTS*NUMCAMERAS],
                int syncOn,
                int syncOff)
{

ofstream ofs;
char outFileName[20];                 // Max. 19 characters plus '\0'

int groundContact;                    // actual row of ground contact

strcpy (outFileName, filename1);      // copies input name to output file name

for (int d = 0; d <= 12; d++)         // loop changes name from KN1 to KN3
    {
    if (outFileName[d] == 'N')
        {
        outFileName[d+1] = '3';
        d = 13;
        } // if
    } // for d

ofs.open(outFileName);

groundContact = footDown(mergedData, syncOff - syncOn + 2);

ofs << 2 << " " << syncOff - syncOn + 2 << " " << groundContact << endl;

for (int i = 0; i < int(FRAMERATE*SAMPLETIME)-5; i++) // print out data
```

```
    {
    for (int j = 0; j < NUMPOINTS*2; j++)
        {
        ofs << mergedData[i][j] << " ";
        } // for j

    ofs << endl;
    } // for i

ofs.close();

} // end function

//**********************************************************************
// This function joins the paths in the middle of the data if no data is availible

void joinPaths(float  mergedData[][NUMCAMERAS*NUMPOINTS])
{

int  startMissing,          // the first missing point
     missingPoints;         // total number of missing points

float xScaleFactor,         // linear interpolation of x data
      yScaleFactor;         // linear interpolation of y data

int endMissing = int(FRAMERATE*SAMPLETIME);  // safety

for (int j = 0; j < NUMPOINTS*2; j = j+2)
    {
                  // loops determine if data is missing
    for (int i = 0; i < int(FRAMERATE*SAMPLETIME); i++)
        {
        if (mergedData[i][j] < 0.5)
            {
            startMissing = i;
            i++;
            while (mergedData[i][j] < 0.5 && i <
                int(FRAMERATE*SAMPLETIME))
                i++;
            endMissing = i - 1;
            }
```

```
if (endMissing + 5 < int(FRAMERATE*SAMPLETIME))
   {

   missingPoints = endMissing - startMissing + 1;

   switch (j*2)
   {
      case (0)  : cout << "Neck data missing. " << missingPoints << "
                  Missing points. Paths being  joined." << endl;
                  break;
      case (2)  : cout << "Hip data missing. " << missingPoints << "
                  Missing points. Paths being joined." << endl;
                  break;
      case (4)  : cout << "Knee data missing. " << missingPoints << "
                  Missing points. Paths being joined." << endl;
                  break;
      case (6)  : cout << "Ankle data missing. " << missingPoints << "
                  Missing points. Paths being joined." << endl;
                  break;
      case (8)  : cout << "Toe data missing. " << missingPoints << "
                  Missing points. Paths being joined." << endl;
                  break;
   } // switch

                        // factors determine intepolation factor
   xScaleFactor = (mergedData[endMissing+1][j]-
      mergedData[startMissing-1][j])  /float(missingPoints+1);
   yScaleFactor = (mergedData[endMissing+1][j+1]-
      mergedData[startMissing-]  [j+1]) /float(missingPoints+1);

               // loop fills in missing data
   for (int k = startMissing; k <= endMissing; k++)
      {
      mergedData[k][j] = mergedData[k-1][j] + xScaleFactor;
      mergedData[k][j+1] = mergedData[k-1][j+1] + yScaleFactor;
      } // for k
   endMissing = int(FRAMERATE*SAMPLETIME);
   } // if endMissing

} // for i
```

```
    } // for j

} // end of function

//*************************************************************************
// This function determines the end of a stride, when the ipsolateral foot
// strike occurs and cuts off the data two frames after that point.
// This function is called from the print function and allows the user to
// look at the data to best determine when ground contact has occured.

int footDown(float mergedData[][NUMCAMERAS*NUMPOINTS],
    int toeOff)        // frame number toe comes off the force plate

{
int groundContact = FRAMERATE*SAMPLETIME-4;
int toeStopFrame,
    lowToeFrame,
    positionStart,
    positionEnd;

float toeStop = 1000.0;
float lowToe = 1000.0;
float highAccel,
     accelNum;

int answer = 1;
int endLoop;

cout << "stance phase is " << toeOff << " frames of data " << endl;

if (int(FRAMERATE*SAMPLETIME*0.8) < toeOff*5)
    endLoop = int(FRAMERATE*SAMPLETIME*0.8);
else
    endLoop = toeOff*5;

                // loop checks area 2nd ground contact is likely to occur
for (int c = toeOff*2; c < int(FRAMERATE*SAMPLETIME*0.8); c++)
    {
    if (mergedData[c+5][TOEMARKER*2-2] -
mergedData[c][TOEMARKER*2-2] < toeStop)
        {
```

```
            if (mergedData[c][TOEMARKER*2-2] > 1.0 &&
                mergedData[c+5][TOEMARKER*2-2] > 1.0)
                {
                toeStop = mergedData[c+5][TOEMARKER*2-2] -
                            mergedData[c][TOEMARKER*2-2];
                toeStopFrame = c;
                }
            }
        } // for c

    cout << "toestop is " << toeStopFrame << endl;

                // searches for the time when the toe is 1 cm off the low point
    for (int b = toeStopFrame-15; b < toeStopFrame+5; b++)
        {
        if (mergedData[b][TOEMARKER*2-1] < lowToe)
            lowToeFrame = b;
        }

    int d = lowToeFrame;

                // checks when the toe marker crosses a point one cm above the
                // low point and that is considered ground contact
    while (mergedData[d][TOEMARKER*2-1] - 1.0 < mergedData[toeStopFrame]
        [TOEMARKER*2-1] && d > toeStopFrame - toeOff)
        {
        d = d-1;
        }

    cout << "1 cm above the low toe frame is " << d << endl;

        highAccel = -.5;

    for (int g = toeStopFrame - int(float(toeOff*.75)); g <= toeStopFrame; g++)
        {
        accelNum = (mergedData[g-1][TOEMARKER*2-1] - 2*mergedData[g]
            [TOEMARKER*2-1] + mergedData[g+1][TOEMARKER*2-1]);

       if (accelNum > highAccel)
        {
        cout << "At frame " << g << " X, Y, Accel " << mergedData[g]
```

```
        [TOEMARKER*2-2] << " " << mergedData[g][TOEMARKER*2-1]
        << " " << accelNum << endl;
    highAccel = accelNum;
    groundContact = g;
        }

    } // for g

while (answer == 1)  // allows user to search for more accurate ground contact
    {
    cout << endl;
    cout << "Ground contact happens at position " << groundContact << endl;
    cout <<"This means stride frequency is " << 60.0*1.0/
        (float(groundContact/200.0)) << " strides/minute" << endl << endl;
    cout << "Do you like the ground contact selected by the computer? " << endl;
    cout << " Type 1 for no and 2 for yes." << endl;
    cin >> answer;
    if (answer == 1)
        {
        cout << "Select an area to search.  What is the position " << endl;
        cout << "number you would like to start with?" << endl;
        cin >> positionStart;
        cout << "What is the position you would like to end with?" << endl;
        cin >> positionEnd;

        highAccel = 0.0;

        for (int h = positionStart; h <= positionEnd; h++)
        {
        accelNum = (mergedData[h-1][TOEMARKER*2-1] -
                        2*mergedData[h][TOEMARKER*2-1] +
                        mergedData[h+1][TOEMARKER*2-1]);

        cout << "At frame " << h << " X, Y, Accel " <<mergedData[h]
        [TOEMARKER*2-2] << " " << mergedData[h][TOEMARKER*2-1]
        << " " << accelNum << endl;

        if (accelNum > highAccel)
            {
            highAccel = accelNum;
            groundContact = h;
```

```
            }

        } // for h

     } // if answer is no

   } // while answer is no

returngroundContact;

} // end function

//**********************************************************************
// This function inputs an int into the string for opening file names

void intoString(char filename[], int n, int counter)
{

int n1,
    newCounter;

newCounter=counter;
n1 = n;

switch (newCounter)
        {
            case (1)  : filename[n1] = '1';
                        break;
            case (2)  : filename[n1] = '2';
                        break;
            case (3)  : filename[n1] = '3';
                        break;
            case (4)  : filename[n1] = '4';
                        break;
            case (5)  : filename[n1] = '5';
                        break;
            case (6)  : filename[n1] = '6';
                        break;
            case (7)  : filename[n1] = '7';
                        break;
            case (8)  : filename[n1] = '8';
```

```
                break;
case (9)  : filename[n1] = '9';
                break;
case (10)  : filename[n1] = '1';
                 filename[n1+1] = '0';
                 break;
case (11)  : filename[n1] = '1';
                 filename[n1+1] = '1';
                 break;
case (12)  : filename[n1] = '1';
                 filename[n1+1] = '2';
                 break;
case (13)  : filename[n1] = '1';
                 filename[n1+1] = '3';
                 break;
case (14)  : filename[n1] = '1';
                 filename[n1+1] = '4';
                 break;
case (15)  : filename[n1] = '1';
                 filename[n1+1] = '5';
                 break;
case (16)  : filename[n1] = '1';
                 filename[n1+1] = '6';
                 break;
case (17)  : filename[n1] = '1';
                 filename[n1+1] = '7';
                 break;
case (18)  : filename[n1] = '1';
                 filename[n1+1] = '8';
                 break;
case (19)  : filename[n1] = '1';
                 filename[n1+1] = '9';
                 break;
case (20)  : filename[n1] = '2';
                 filename[n1+1] = '0';
                 break;
case (21)  : filename[n1] = '2';
                 filename[n1+1] = '1';
                 break;
case (22)  : filename[n1] = '2';
                 filename[n1+1] = '2';
```

```
                break;
case (23)  : filename[n1] = '2';
                filename[n1+1] = '3';
                break;
case (24)  : filename[n1] = '2';
                filename[n1+1] = '4';
                break;
case (25)  : filename[n1] = '2';
                filename[n1+1] = '5';
                break;
case (26)  : filename[n1] = '2';
                filename[n1+1] = '6';
                break;
case (27)  : filename[n1] = '2';
                filename[n1+1] = '7';
                break;
case (28)  : filename[n1] = '2';
                filename[n1+1] = '8';
                break;
case (29)  : filename[n1] = '2';
                filename[n1+1] = '9';
                break;
case (30)  : filename[n1] = '3';
                filename[n1+1] = '0';
                break;
case (31)  : filename[n1] = '3';
                filename[n1+1] = '1';
                break;
case (32)  : filename[n1] = '3';
                filename[n1+1] = '2';
                break;
case (33)  : filename[n1] = '3';
                filename[n1+1] = '3';
                break;
case (34)  : filename[n1] = '3';
                filename[n1+1] = '4';
                break;
case (35)  : filename[n1] = '3';
                filename[n1+1] = '5';
                break;
case (36)  : filename[n1] = '3';
```

```
                filename[n1+1] = '6';
                break;
        case (37) : filename[n1] = '3';
                filename[n1+1] = '7';
                break;
        case (38) : filename[n1] = '3';
                filename[n1+1] = '8';
                break;
        case (39) : filename[n1] = '3';
                filename[n1+1] = '9';
                break;
        case (40) : filename[n1] = '4';
                filename[n1+1] = '0';
                break;
    } // switch

} // end of function
```

```
//************************************************************************
//
//                                                        Kinetic.cpp
// Alan W. Arata,                                         25 Oct 98
//
//************************************************************************
// This program takes the data from APAS and determines stance time,
// time at max impact peak, force at impact peak, time at max impulse peak,
// maximum slope during impact and initial braking/propulsion forces.
// Important variable set as global variables are listed below.
// This program assumes the data is ordered FZ, FY, FX and disregards the
// FX data. The pretrigger must be set to 5% of the sample time or
// HEADERLINES will be incorrect.

#include <iostream.h>
#include <math.h>           // for sqrt function
#include <fstream.h>            // for file i/o redirection
#include <stdlib.h>             // for exit
#include <iomanip.h>        // for set precision

const int NUMSUBJECTS = 35;        // maximum number of subjects
const int NUMCONDTIONS = 5;        // # of conditions - BRmax, BR80, BR60,
                                   FRmax, FReq
const int NUMTRIALS = 3;           // number of trials
const int NUMCHANNELS = 2;         // # of channels to be read into array
const int HEADERLINES = 30;        // # of APAS header lines
const int NUMPARAMETERS = 9;       // # of parameters such as stance time
const int SAMPLERATE = 1000;       // sample rate in Hz

const float SAMPLETIME = 0.4;// time sampled

void intoString(char[], int, int);
void getWeights(float[], int); // gets an array of subject's weights
void openfiles(char[],float[][NUMCHANNELS], float[], int);

void stanceTime(float[][NUMCHANNELS], float[][NUMPARAMETERS],
float[], int, int);
void impact(float[][NUMCHANNELS], float[][NUMPARAMETERS], float[],
int);
void impactSlope(float[][NUMCHANNELS], float[][NUMPARAMETERS],
int);
```

```
void impulse(float[][NUMCHANNELS], float[][NUMPARAMETERS], int);
void initialAccel(float[][NUMCHANNELS], float[][NUMPARAMETERS],
int);
void finalBraking(float[][NUMCHANNELS], float[][NUMPARAMETERS],
int);
void deltaVel(float[][NUMCHANNELS], float[][NUMPARAMETERS], int);

void main()
{
ofstream ofs;

float forceData[int(SAMPLETIME*SAMPLERATE)][NUMCHANNELS];
float subjectWeights[NUMSUBJECTS];
float outputData[NUMTRIALS][NUMPARAMETERS];

int subjectStart,
    subjectEnd,
    conditionStart,
    conditionEnd;

float avg;                    // average data of the trials

char filename[15];            // Max. 15 characters plus '\0'
char abort;                   // allow user to abort

cout << "Program assumes that the files are listed in the format of" << endl;
cout << "S1C1T1.PRN" << endl << endl;

cout <<"What subject number do you want to start with?" << endl;
cin >> subjectStart;

cout <<"What subject number do you want to end with?" << endl;
cin >> subjectEnd;

cout <<"What condition number do you want to start with?" << endl;
cin >> conditionStart;

cout <<"What condition number do you want to end with?" << endl;
cin >> conditionEnd;

getWeights(subjectWeights, subjectEnd);
```

```
cout << "Trials are automatically between 1 and " << NUMTRIALS << endl;
cout << "Weight file name is subwgt.  If this is not correct press q."  << endl;
cout << "If any parameters is incorrect, enter q otherwise r and return" <<
endl;

cin >> abort;

while (abort != 'q' && abort != 'Q')  // loop allows user to quit program
    {
    ofs.open("As32kinetic.xls");
    ofs << "File, Stance t, Impact peak, Impact t, Impact slope, F2,";
    ofs << "F2 time, I Accel f, F braking f,";
    ofs << "Accel index" << endl;
    ofs << "Name, ms, BW, % stance t, BW/sec, BW, % stance t,";
    ofs << "% BW, % BW, % factor" << endl;

    for (int i = subjectStart; i <= subjectEnd; i++)  // loops place the file
        {                                             // name in a string format
        int n = 0;
        filename[n] = 'S';
        n++;
        intoString(filename, n, i);
        n++;
        if (i > 9)
            n++;
        filename[n] = 'C';
        n++;
                                // loop places condition number in string
        for (int j = conditionStart; j <= conditionEnd; j++)
            {
            intoString(filename, n, j);
            n++;
            if (j > 9)
                n++;
            filename[n] = 'T';
            n++;
                                // loops intialize output array to 0's
            for (int f = 0; f < NUMTRIALS; f++)
                for (int g = 0; g < NUMPARAMETERS; g++)
                    outputData[f][g] = 0.0;
```

```
for (int k = 1; k <= NUMTRIALS; k++) // places trial #'s in string
    {                                    // and call the functions
    intoString(filename, n, k);
    n++;
    if (k > 9)
        n++;
    filename[n] = '.';
    n++;
    filename[n] = 'P';
    n++;
    filename[n] = 'R';
    n++;
    filename[n] = 'N';
    n++;
    filename[n] = '\0';

    ofs << filename << ",";

    openfiles(filename, forceData, subjectWeights, i);
    stanceTime(forceData, outputData, subjectWeights, k-1, i);
    impact(forceData, outputData, subjectWeights, k-1);
    impactSlope(forceData, outputData, k-1);
    impulse(forceData, outputData, k-1);
    initialAccel(forceData, outputData, k-1);
    finalBraking(forceData, outputData, k-1);
    deltaVel(forceData, outputData, k-1);

    for (int r = 0; r < NUMPARAMETERS; r++)
        {
            ofs << outputData[k-1][r] << ",";
        } // for r
    ofs << endl;

    n = n-5;

    } // for k

for (int p = 0; p <= n-2; p++)
    ofs << filename[p];
ofs << " Average" << ",";
```

```
            for (int m = 0; m < NUMPARAMETERS; m++)
                {
                if (outputData[0][m] == -1 || outputData[1][m] == -1 ||
                   outputData[2][m] == -1)
                    avg = -1;
                else
                    avg = (outputData[0][m] + outputData[1][m] +
                      outputData[2][m])/NUMTRIALS;

                ofs << avg << ",";

                } // for m

            ofs << endl << endl;

            cout << endl;

            n = n-2;

            } // for j

    } // end of for i statement

    ofs.close();

    abort = 'q';  // ends loop

    } // end of while not q

} // end of main

//************************************************************************
// This function retrieves the data base of subjects weights that the user
// set up.  All weights must be in Newtons for proper calculations.

void getWeights(float subjectWeights[], int subjectEnd)
{

ifstream ifs;
```

```
int subNum;                 // subject number listed before weight in file

ifs.open("subwgt");         // open the output file stream

if (ifs.fail())             // check for success
    {
    cout << "Error input file stream -- existing." << endl;
    exit (1);
    }

for (int c = 0; c < NUMSUBJECTS; c++)
    {
    ifs >> subNum >> subjectWeights[c];
    }

ifs.close();

} // end function

//************************************************************************
// This function retrieves an existing data base from an APAS PRN output.
// The function will skip the first set of lines until it gets to the data.
// It will then read the data into a 3D array for easy manipulation.

void openfiles(char filename[],
               float forceData[][NUMCHANNELS],
               float subjectWeights[],  // array of subject weights
               int subjectsNumber)      // subject number is equal to i
{

ifstream ifs;

int j = 0;              // while loop counter

float time,             // time from data
      Fz,               // Fz value from data
      Fx,               // Fx value from data
      Fy;               // Fy vaule from data

ifs.open(filename);     // open the output file stream
```

```
if (ifs.fail())              // check for success
    {
    cout << "Error opening input file stream -- existing." << endl;
    exit (1);
    }

cout << filename << " currently being processed" << endl;

for (int c = 1; c <= HEADERLINES; c++)  // eats the APAS header lines
    ifs.ignore(100,'\n');

ifs >> time >> Fz >> Fy >> Fx;

while (Fz < 25.0 && ifs)
    ifs >> time >> Fz >> Fy >> Fx;

forceData[j][0] = Fz/subjectWeights[subjectsNumber-1];
forceData[j][1] = (Fy * -1.0)/subjectWeights[subjectsNumber-1];
j++;

while (time < SAMPLETIME)
    {
    ifs >> time >> Fz >> Fy >> Fx;
    forceData[j][0] = Fz/subjectWeights[subjectsNumber-1];
    forceData[j][1] = (Fy * -1.0)/subjectWeights[subjectsNumber-1];
    j++;
    }

ifs.close();

} // end function

//**********************************************************************
// This functions determines the stance time length
//

void stanceTime(float forceData[][NUMCHANNELS],
                float  outputData[][NUMPARAMETERS],
                float subjectWeights[],
                int trialNumber,         // variable k - 1
                int subjectsNumber)      // subject number is equal to i
```

```
{

int c = 30;              // loop counter

while (forceData[c][0] > (20.0/subjectWeights[subjectsNumber-1])
              && c < int(SAMPLETIME*SAMPLERATE))
    {
    c++;
    }

outputData[trialNumber][0] = float(c);

} // end function


//***********************************************************************
// This function determines magnitude and percent time of the impact force
// Note file is desinged to look for impact within the first 22% stance time

void impact(float forceData[][NUMCHANNELS],
            float  outputData[][NUMPARAMETERS],
            float subjectWeights[],
            int trialNumber)    // variable k - 1
{

float resultantForce1,      // resultant force from Fz and Fy
      resultantForce2,      // resultant force from Fz and Fy
      time2peak,            // time to reach the peak force
      peak = 0;             // max resultant force from Fz and Fy

int upcounter;

resultantForce1 =
sqrt(forceData[3][0]*forceData[3][0]+forceData[3][1]*forceData[3][1]);

for (int c = 4; c < int(0.22*outputData[trialNumber][0]); c++)
    {
    resultantForce2 =
    sqrt(forceData[c][0]*forceData[c][0]+forceData[c][1]*forceData[c][1]);

    if (resultantForce2 > resultantForce1)
```

```
        {
        resultantForce1 = resultantForce2;
        upcounter=c;
        }
    else
        if (c >= upcounter + 2)    // requires two lower points of data to be
            {                      // considered a peak
            peak = resultantForce1;
            time2peak = float(upcounter);
            }

    } // for c

if (peak -
sqrt(forceData[0][0]*forceData[0][0]+forceData[0][1]*forceData[0][1]) < .04)
    {
    outputData[trialNumber][1] = -1.0;     // denotes no impact peak
    outputData[trialNumber][2] = -1.0;     // denotes no time at impact peak
    }
else
    {
    outputData[trialNumber][1] = peak;
    outputData[trialNumber][2] =
100*float(time2peak)/outputData[trialNumber][0];
    }

} // end function

//************************************************************************
// This function finds the impact peaks maximum slope.  Again it assumes the
// impact peak occurs within the first 15%  of stance time

void impactSlope(float forceData[][NUMCHANNELS],
            float  outputData[][NUMPARAMETERS],
            int trialNumber)            // variable k -1
{
float pointOne,                         // resultant force of first point
     pointTwo;                          // resultant force of 2nd point

//  Calculates the average slope over 2 ms then divides it by 2
```

```
for (int c = 5; c <= int(0.15*outputData[trialNumber][0]); c++)
    {
    pointOne = sqrt(forceData[c-2][0]*forceData[c-2][0]+
        forceData[c-2][1]*forceData[c-2][1]);
    pointTwo =
        sqrt(forceData[c][0]*forceData[c][0]+forceData[c][1]*forceData[c][1]);
    if (((pointTwo - pointOne)/2)*1000.0 > outputData[trialNumber][3])
        outputData[trialNumber][3] = ((pointTwo - pointOne)/2)*1000.0;

    } // end of for c

} // end function

//************************************************************************
// This function finds the largest impulse value and the percentage time it
// occured during the stride.

void impulse(float forceData[][NUMCHANNELS],
            float outputData[][NUMPARAMETERS],
            int trialNumber)                    // variable k
{
float resultantForce;
                                // searches last 70% of stance
for (int c = int(.30*outputData[trialNumber][0]);
        c < int(outputData[trialNumber][0])-1; c++)
    {
    resultantForce =
        sqrt(forceData[c][0]*forceData[c][0]+forceData[c][1]*forceData[c][1]);
    if (resultantForce > outputData[trialNumber][4])
        {
        outputData[trialNumber][4] = resultantForce;
        outputData[trialNumber][5] = 100.0*(float(c)/
            outputData[trialNumber][0]);
        }

    } // end of for c

} // end function

//************************************************************************
// This function determines the maximum value of the initial acceleration
```

```
// force from the Fy curve if one exist

void initialAccel(float forceData[][NUMCHANNELS],
            float outputData[][NUMPARAMETERS],
            int trialNumber)                    // variable k
{
if (forceData[3][1] > 0.0)
   {
   for (int c = 0; c < int(.15*outputData[trialNumber][0]); c++)
      if (forceData[c][1] > outputData[trialNumber][6])
      outputData[trialNumber][6] = forceData[c][1];
   }

outputData[trialNumber][6] = outputData[trialNumber][6]*100.0;
} // end function

//*******************************************************************
// The function determines the maximum braking force just before foot off

void finalBraking(float forceData[][NUMCHANNELS],
            float outputData[][NUMPARAMETERS],
            int trialNumber)                    // variable k
{
for (int c = int(outputData[trialNumber][0])-40;
      c < int(outputData[trialNumber][0])-1; c++)

   if (forceData[c][1] < outputData[trialNumber][7])
      outputData[trialNumber][7] = forceData[c][1];

outputData[trialNumber][7] = outputData[trialNumber][7]*100.0;
} // end function

//*******************************************************************
// The function determines if the individual is accelerating or decelerating
// when crossing the force plate

void deltaVel(float forceData[][NUMCHANNELS],
            float outputData[][NUMPARAMETERS],
            int trialNumber)                    // variable k
{
float negVelSum = 0.0;
```

```
float posVelSum = 0.0;

for (int c = 0; c < int(outputData[trialNumber][0]); c++)
    {
    if (forceData[c][1] > 0.0001)
        posVelSum = posVelSum + forceData[c][1];
    else
        negVelSum = negVelSum + forceData[c][1];
    }

    if (posVelSum > negVelSum)
        outputData[trialNumber][8] = posVelSum/negVelSum;
    else
        outputData[trialNumber][8] = negVelSum/posVelSum;

} // end function

//**********************************************************************
// This function inputs an int into the string for opening file names

// see intoString in the combine.cpp program for fuction
```

```
//*********************************************************************
//
//                                              Kinematic.cpp
// Alan W. Arata,                               6 Nov 98
//
//*********************************************************************

// This program takes the data the combine.cpp and determines stride length,
// stride frequency, maximum hip, knee, and ankle angles and % of stride
// at which they occur. It also caculates maximum hip and knee accelerations.
// Several global variables are set up just below and may need to be changed if
// this program is used for something different than Alan Arata's disertation.
// data. This program outputs, velocity, stride length, stride frequency, the
// trunk angle at ground contact (GC), the trunk angle at foot off (FO),
// maximum hip angle & time of occurance, maximum knee angle & time of,
// occurance maximum ankle angle & time of occurance, minimum hip angle &
// time of occurance,minimum knee angle & time of occurance, min ankle angle
// & time of occurance,hip angle at GC, hip angle at FO, knee angle at GC, knee
// angle at FO,ankle angle at GC, ankle angle at FO, hip angular velocity at
// GC,hip angular velocity at FO, knee angular velocity at GC, knee angular
// velocity at FO, ankle angular velocity at GC, ankle angular velocity at FO,
// change in height over one stride, the maximum horizontal velocity of the
// ankle,the maximum horizontal acceleration of the ankle, the subjects leg
// length,the distance between the ankle and hip at GC and TO acutual and as
// a percentage of leg length.

#include <iostream.h>
#include <math.h>                 // for trig functions
#include <fstream.h>              // for file i/o redirection
#include <stdlib.h>               // for exit
#include <iomanip.h>              // for set precision

const int NUMSUBJECTS = 30;          // maximum number of subjects
const int NUMCONDTIONS = 5;          // number of conditions - BRmax,
BR80, BR60, FRmax, FReq
const int NUMPARAMETERS = 40;     // number of parameters
const int NUMMARKERS = 5;  // five marks not counting sync light
const int NUMCAMERAS = 2;  // number of cameras to be merged
const int NUMTRIALS = 3;        // number of trials
const int NECK_X = 0;           // X coordinates of neck marker in data array
const int NECK_Y = 1;           // Y coordinates of neck marker in data array
```

```
const int HIP_X = 2;            // X coordinates of hip marker in data array
const int HIP_Y = 3;            // Y coordinates of hip marker in data array
const int KNEE_X = 4;           // X coordinates of knee marker in data array
const int KNEE_Y = 5;           // Y coordinates of knee marker in data array
const int ANKLE_X = 6;          // X coordinates of ankle marker in data array
const int ANKLE_Y = 7;          // Y coordinates of ankle marker in data array
const int TOE_X = 8;            // X coordinates of toe marker in data array
const int TOE_Y = 9;            // Y coordinates of toe marker in data array

const float SAMPLETIME = 0.9;      // total video time needed
const float FRAMERATE = 200.0;        // frame rate in Hz

void intoString(char[], int, int);
void openfiles(char[],float[][2*NUMMARKERS], int&, int&, int&);

void strideLenFreq(float[][2*NUMMARKERS], float[][NUMPARAMETERS], int, int,
int);
void trunkAngle(float[][2*NUMMARKERS], float[][NUMPARAMETERS], int, int, int);
void jointAngle(float[][2*NUMMARKERS], float[][NUMPARAMETERS], int, int, int);
void gcJointAngle(float[][2*NUMMARKERS], float[][NUMPARAMETERS], int, int,
int);
void angleVel(float[][2*NUMMARKERS], float[][NUMPARAMETERS], int, int, int);
void height(float[][2*NUMMARKERS], float[][NUMPARAMETERS], int, int, int);
void ankleAV(float[][2*NUMMARKERS], float[][NUMPARAMETERS], int, int, int);
void horExtend(float[][2*NUMMARKERS], float[][NUMPARAMETERS], int, int, int);

float getAngle(float[][2*NUMMARKERS], int, int, int);

int outCount;           // **global counter for each time through the k loop

void main()
{
ofstream ofs;

float kinematicPoints[int(SAMPLETIME*FRAMERATE)][2*NUMMARKERS];
// kinematicPoints is the 3D array of kinematic points from the KN3 file

float  outputData[NUMTRIALS][NUMPARAMETERS];
// outputData is the data for the output file, key items of interest

int subjectStart,       // first subject data to be processed
    subjectEnd,         // last subject data to be processed
    conditionStart,     // first condition number to be processed
```

```
    conditionEnd,         // last condition number to be processed
    syncOn,               // array index when sync light is on
    syncOff,              // array index when sync light is off
    groundContact;        // ipsilateral ground contact

float avg;                // average data of the trials

char filename[20];        // input file name -- max.19 characters plus '\0'
char outFileName[20];     // input file name -- max.19 characters plus '\0'
char abort;               // allow user to abort main program

cout << "Program assumes that the files are listed in the format of" << endl;
cout << "S1C1T1.KN3" << endl << endl;

cout <<"What subject number do you want to start with?" << endl;
cin >> subjectStart;

cout <<"What subject number do you want to end with?" << endl;
cin >> subjectEnd;

cout <<"What condition number do you want to start with?" << endl;
cin >> conditionStart;

cout <<"What condition number do you want to end with?" << endl;
cin>>conditionEnd;

cout << "Trials is automatically between 1 and " << NUMTRIALS << endl;
cout << "If parameters are incorrect, enter q otherwise press r and return" <<
endl;

cin >> abort;

while (abort != 'q' && abort != 'Q')
    {
    cout << "Please provide a name for the output data." << endl;
    cin >> outFileName;

    ofs.open(outFileName);
    ofs << "Sub, Cond,Vel,Stride length,Stride Freq,T ang at GC,T ang at FO, H ";
    ofs << "max ang,H max occur,K max ang,K max occur,A max angle,A max
occur,";
```

```
    ofs << "H min ang,H Min occur,K min ang,K min occur,A min ang,A min occur,";
    ofs << "H at GC,H at FO,K and GC,K at FO,A at GC,A at FO,H vel GC,";
    ofs << "H vel FO, K vel GC, K vel FO, A vel GC, A vel FO,Delta height,A maxV,";
    ofs << "A max Acc,leg length,X dis at GC,X dis at GC,X dis at FO,X dis at FO"  <<
endl;
    ofs << "#,#,m*s-1,cm,Strides*m-1,deg,deg,deg,% Stride,deg,% Stride,";
    ofs << "deg,% Stride,deg,% Stride,deg,% Stride,";
    ofs << "deg,% Stride,deg,deg,deg,deg,deg,deg,";
    ofs <<  "deg*s-1,deg*s-1,deg*s-1,deg*s-1,deg*s-1,deg*s-1,";
    ofs << "cm, m*s-1,m*s-2,cm,cm,% leg length,cm,% leg length" << endl;

    for (int i = subjectStart; i <= subjectEnd; i++)      // loops place the file
        {                                                // name in a string format
        int n = 0;                                       // placement counter for
filename string
        filename[n] = 'S';
        n++;
        intoString(filename, n, i);
        n++;
        if (i > 9)                                       // in case sub # is > 9
            n++;
        filename[n] = 'C';
        n++;

        for (int j = conditionStart; j <= conditionEnd; j++)
            {
            intoString(filename, n, j);
            n++;
            if (j > 9)                                   // in case cond # is > 9
                n++;
            filename[n] = 'T';
            n++;

                    // loops initialize the array to 0.0
            for (int f = 0; f < NUMTRIALS; f++)
                for (int g = 0; g < NUMPARAMETERS; g++)
                    outputData[f][g] = 0.0;

            for (int k = 1; k <= NUMTRIALS; k++)
                {
                outCount = 0;
```

```
intoString(filename, n, k);
n++;
if (k > 9)                              // in case trial # is > 9
    n++;
filename[n] = '.';
n++;
filename[n] = 'K';
n++;
filename[n] = 'N';
n++;
filename[n] = '3';
n++;
filename[n] = '\0';

openfiles(filename, kinematicPoints, syncOn, syncOff,
    groundContact);

strideLenFreq(kinematicPoints, outputData, syncOn,
    groundContact, k);
trunkAngle(kinematicPoints, outputData, j, k, syncOn);
trunkAngle(kinematicPoints, outputData, j, k, syncOff);
jointAngle(kinematicPoints, outputData, j, k, groundContact);
gcJointAngle(kinematicPoints, outputData, j, k, syncOn);
gcJointAngle(kinematicPoints, outputData, j, k, syncOff);
angleVel(kinematicPoints, outputData, j, k, syncOn);
angleVel(kinematicPoints, outputData, j, k, syncOff);
height(kinematicPoints, outputData, k, syncOn, syncOff);
ankleAV(kinematicPoints, outputData, k, syncOff,
    groundContact);
horExtend(kinematicPoints, outputData, k, syncOn, syncOff);

        // loops break filename and conditions into different
        // MicroSoft excel columns for easy sorting
for (int z = 0; z <= 3; z++)
    {
    if (filename[z] != 'C')
        ofs << filename[z];
    else
        {
        ofs << ",";
        break;
```

```
            }
        } // for z

    while (filename[z] != '\0' && z < 16)
        {
        ofs << filename[z];
        z++;
        }

    ofs << ",";

            // loop prints out key parameters selected by program
    for (int r = 0; r < NUMPARAMETERS; r++)
        {
            ofs << outputData[k-1][r] << ",";
        } // for r
    ofs << endl;

    n = n-5;

    } // for k

        // loops set up average data by condition
for (int p = 0; p <= 3; p++)
    {
    if (filename[p] != 'C')
        ofs << filename[p];
    else
        {
        ofs << ",";
        break;
        }
    } // for p

    while (p <= n-2)
        {
        ofs << filename[p];
        p++;
        }

ofs << ".AVG" << ",";
```

```
            for (int m = 0; m < NUMPARAMETERS; m++)
                {
                avg = (outputData[0][m] + outputData[1][m] +
                        outputData[2][m])/NUMTRIALS;
                ofs << avg << ",";
                } // for m

            ofs << endl << endl;

            cout << endl;

            n = n-2;

            } // for j

    } // end of for i statement

    ofs.close();

    abort = 'q';  // ends loop

    } // end of while not q

} // end of main

//************************************************************************
// This function retrieves a data sheet made by the combine.cpp program.
// the data should be listed with the sync light on row #, followed by the
// sync light off row # followed by ipsilateral ground contact, is the data
// with Xneck, Yneck, Xhip, Yhip, Xknee, Yknee, Xankle, Yankle, Xfoot, Yfoot.

void openfiles(char filename[],
            float kinematicPoints[][2*NUMMARKERS],
            int& syncOn,            // initial ground contact
            int& syncOff,           // initial foot off
            int& groundContact)     // ipsilateral 2nd ground contact
{

ifstream  ifs;                      // input from a file
```

```
ifs.open(filename);                     // open the output file stream

if (ifs.fail())                         // check for success
    {
    cout << "Error opening input file stream -- existing." << endl;
    exit (1);
    }

cout << filename << " currently being processed." << endl;

ifs >> syncOn >> syncOff >> groundContact;

            // loops read in data from KN3 file
for (int c = 0; c <= groundContact + 2; c++)
    for (int d = 0; d < 2*NUMMARKERS; d++)
        ifs >> kinematicPoints[c][d];

ifs.close();

} // end function

//************************************************************************
// This function determines the velocity, stride length and stride frequency
// and places them into the output array.

void strideLenFreq(float kinematicPoints[][2*NUMMARKERS],
                   float outputData[][NUMPARAMETERS],
                   int syncOn,          // initial ground contact
                   int groundContact,   // ipsilateral 2nd ground contact
                   int trialNum)        // k from main program loop
{
                                        // velocity
outputData[trialNum-1][outCount] = ((kinematicPoints[((groundContact + 1)
    - syncOn)][HIP_X] - kinematicPoints[syncOn][HIP_X])/100.0) *
    FRAMERATE/ (float((groundContact + 1) - syncOn));
outCount++;
                                        // stride length
outputData[trialNum-1][outCount] = kinematicPoints[groundContact]
    [HIP_X] - kinematicPoints[syncOn][HIP_X];
outCount++;
                                        // stride frequency
```

```
outputData[trialNum-1][outCount] = 60*(1/(float(groundContact - syncOn +
1)/FRAMERATE));

outCount++;

} // end function

//************************************************************************
// This function determines the trunk angle with respect to the 360 degree
// vertical position given a frame number.

void trunkAngle(float kinematicPoints[][2*NUMMARKERS],
                float  outputData[][NUMPARAMETERS],
                int condNum,        // j from input array
                int trialNum,       // k from input array
                int sync)           // syncOn or syncOff

{

float angle;                        // computated joint angle

angle = atan((kinematicPoints[sync][NECK_X] - kinematicPoints[sync]
        [HIP_X])/ (kinematicPoints[sync][NECK_Y] -
        kinematicPoints[sync][HIP_Y]))*57.3;

outputData[trialNum-1][outCount] = angle;

outCount++;

} // end trunkAngle function

//************************************************************************
// This functions determines the angles of the hip, knee and ankle.  Since it
// designed for backward and forward running, it is very specific for this use.
// The actual algorithm can be used to determine angles not in the same
// quadrant,but the if statement is specifically set for the Backward running
// dissertation

void jointAngle(float  kinematicPoints[][2*NUMMARKERS],
                float outputData[][NUMPARAMETERS],
                int conditionNumber,     // j from input array
```

```
                    int trialNum,           // k from input array
                    int groundContact)      // ipsilateral 2nd ground contact
{
float angle;                                // computated joint angle

          // sets the hip, knee and ankle angles to 360 degrees
          // for seach fo minimum angle
for (int f = 6; f < 11; f = f+2)
    outputData[trialNum-1][outCount+f] = 360.0;

    // loops go through hip, knee, ankle sequence finding max and min angles
for (int b = 2; b < NUMMARKERS*2-2; b = b+2)
    {
    for (int c = 2; c < groundContact -2; c++)
        {
        angle = getAngle(kinematicPoints, conditionNumber, c, b);

        if (angle > outputData[trialNum-1][outCount] && angle < 200.0)
            {
            outputData[trialNum-1][outCount] = angle;
            outputData[trialNum-1][outCount+1] = 100*(float(c-1)/
                float(groundContact-2));
            }

        if (angle < outputData[trialNum-1][outCount+6])
            {
            outputData[trialNum-1][outCount+6] = angle;
            outputData[trialNum-1][outCount+7] = 100*(float(c-1)/
                float(groundContact-2));
            }

        } // for c

    outCount = outCount+2;

    } // for b

outCount = outCount+6;

} // end function
```

```
//*************************************************************************
// This function determines the joint angles given a specific time within the
// stride such as sincOn or syncOff.

void  gcJointAngle(float  kinematicPoints[][2*NUMMARKERS],
                float  outputData[][NUMPARAMETERS],
                int condNum,             // j from input array
                int trialNum,            // k from input array
                int sync)                // syncOn or syncOff
{

float angle;                             // computated joint angle

          // loop finds joint angle at specified point
for (int b = 2; b < NUMMARKERS*2-2; b = b+2)
   {
   outputData[trialNum-1][outCount] = getAngle(kinematicPoints,
      condNum, sync, b);

   outCount++;

   } // for b

} // end function

//*************************************************************************
//

void  angleVel(float  kinematicPoints[][2*NUMMARKERS],
               float  outputData[][NUMPARAMETERS],
               int condNum,              // j from input array
               int trialNum,             // k from input array
               int rowLocate)            // syncOn or syncOff

{
          // loop finds agular velocity for hip, knee & ankle at
          // specified point
for (int b = 2; b < NUMMARKERS*2-2; b = b+2)
   {
   outputData[trialNum-1][outCount] =
      (getAngle(kinematicPoints, condNum, rowLocate+1, b) -  getAngle
```

```
        (kinematicPoints, condNum, rowLocate-1, b))/(2.0/FRAMERATE);
    outCount++;
    }

} // end function

//**************************************************************************
// This function determines the change in vertical height during a stride

void height(float kinematicPoints[][2*NUMMARKERS],
            float outputData[][NUMPARAMETERS],
            int trialNum,               // k from input array
            int syncOn,                 // same old sync
            int groundContact)          // ipsi gc

{
float highValue = 1.0,                  // highest hip value found
     lowValue = 1000.0;                 // lowest hip value found

            // Loop searches for highest and lowest hip marker over 1 stride
for (int c = syncOn; c <= groundContact; c++)
    {
    if (kinematicPoints[c][HIP_Y] > highValue)
        highValue = kinematicPoints[c][HIP_Y];

    if (kinematicPoints[c][HIP_Y] < lowValue)
        lowValue = kinematicPoints[c][HIP_Y];

    } // for c

outputData[trialNum-1][outCount] = highValue - lowValue;

outCount++;

} // end of height function

//**************************************************************************
// This function determines the  max positive velocity and acceleration
// of the ankle marker

void ankleAV(float kinematicPoints[][2*NUMMARKERS],
```

```
          float  outputData[][NUMPARAMETERS],
          int trialNum,              // k from input array
          int syncOff,               // same old sync
          int groundContact)         // ipsi gc

{
float maxVel = 0.0;                  // highest velocity value found
float maxAccel = 0.0;                // highest acceleration value found
float  ankleVel,                     // velocity for specific frame number
     ankleAcc;                       // acceleration for specific frame number

          // loop searches initial swing phase
for (int c = syncOff; c < int(float(groundContact)*.66); c++)
   {

   ankleVel = (kinematicPoints[c+1][ANKLE_X] -
       kinematicPoints[c-1][ANKLE_X])/ (2.0/FRAMERATE);

   ankleAcc = (kinematicPoints[c+1][ANKLE_X] -  2*kinematicPoints[c]
       [ANKLE_X] +kinematicPoints[c-1][ANKLE_X])/
       ((1.0/FRAMERATE)*(1/FRAMERATE));

   if (ankleVel > maxVel)
       maxVel = ankleVel;

   if (ankleAcc > maxAccel)
       maxAccel = ankleAcc;

   } // end of for c loop

outputData[trialNum-1][outCount] = maxVel/100.0;

outCount++;

outputData[trialNum-1][outCount] = maxAccel/100.0;

outCount++;

} // end ankleAV function

//*********************************************************************
```

```
// This function calculates the horizontal distance the from the hip to the
// ankle during ground contact and toe-off. It reports the values both as a
// percentage of and actual leg length.

void horExtend(float kinematicPoints[][2*NUMMARKERS],
        float outputData[][NUMPARAMETERS],
        int trialNum,       // k from input array
        int syncOn,         // same old sync
        int syncOff)        // ipsi gc

{
float AvgLegLength = 0.0;     // the sum of the leg lengths
float legLength;              // leg length

        // loop determines leg length over a stride
for (int c = syncOn; c <= syncOff; c++)
    AvgLegLength = sqrt((kinematicPoints[c][ANKLE_X] -
        kinematicPoints[c][KNEE_X])*(kinematicPoints[c][ANKLE_X] -
        kinematicPoints[c][KNEE_X])+ (kinematicPoints[c][ANKLE_Y] -
        kinematicPoints[c][KNEE_Y])* (kinematicPoints[c][ANKLE_Y] -
        kinematicPoints[c][KNEE_Y]))+ sqrt((kinematicPoints[c][HIP_X] -
        kinematicPoints[c][KNEE_X])* (kinematicPoints[c][HIP_X] -
        kinematicPoints[c][KNEE_X])+ (kinematicPoints[c][HIP_Y] -
        kinematicPoints[c][KNEE_Y])* (kinematicPoints[c][HIP_Y] -
        kinematicPoints[c][KNEE_Y]))+AvgLegLength;

legLength=AvgLegLength/float(syncOff-syncOn+1);

outputData[trialNum-1][outCount] = legLength;

outCount++;

outputData[trialNum-1][outCount] = (kinematicPoints[syncOn][ANKLE_X] -
                        kinematicPoints[syncOn][HIP_X]);

outCount++;

outputData[trialNum-1][outCount] = 100 * (kinematicPoints[syncOn]
[ANKLE_X] - kinematicPoints[syncOn][HIP_X])/legLength;

outCount++;
```

```
outputData[trialNum-1][outCount] = (kinematicPoints[syncOff][HIP_X] -
                                    kinematicPoints[syncOff][ANKLE_X]);

outCount++;

outputData[trialNum-1][outCount] = 100 * (kinematicPoints[syncOff][HIP_X]
    -kinematicPoints[syncOff][ANKLE_X])/legLength;

outCount++;

} // end function horExtend

//***********************************************************************
// This function returns an angle given a specific location, such as
// ground contact or toe-off

float getAngle(float kinematicPoints[][2*NUMMARKERS],
            int condNum,        // j from main loop
            int row,            //array row pointer
            int col)            //array column pointer

{
float angle;                    // computated joint angle

if (kinematicPoints[row][col-1] > kinematicPoints[row][col+1])
    {
    angle = atan((kinematicPoints[row][col-2] - kinematicPoints[row][col])/
        (kinematicPoints[row][col-1] - kinematicPoints[row][col+1]))*57.3;
    }
else
    angle = 180 - atan((kinematicPoints[row][col] - kinematicPoints[row]
[col-2])/ (kinematicPoints[row][col-1] - kinematicPoints[row][col+1]))*57.3;


// Above is for the top and center points of the angle, below is for the center
// and lower points of the angle--though the top may not be higher than the
// lower depending on the position of the body.

if (kinematicPoints[row][col+3] > kinematicPoints[row][col+1])
    {
```

```
    if (kinematicPoints[row][col] < kinematicPoints[row][col+2])
        angle = atan((kinematicPoints[row][col] - kinematicPoints[row][col+2])/
        (kinematicPoints[row][col+1] - kinematicPoints[row][col+3]))*57.3-
angle;
   else
    angle = 360 + atan((kinematicPoints[row][col] - kinematicPoints[row]
        [col+2])/ (kinematicPoints[row][col+1] - kinematicPoints[row][col+3]))
        *57.3 - angle;
   }
else
    angle = 180 - atan((kinematicPoints[row][col+2] - kinematicPoints[row]
        [col])/ (kinematicPoints[row][col+1] - kinematicPoints[row][col+3]))
        *57.3 - angle;

    // folloiwing if statement is required because backward running angle
    // are opposite of forward angles
if (condNum <= 3 && col == 2 ||
    condNum <= 3 && col == 6 ||
    condNum  > 3 && col == 4)
    {
    angle = 360 - angle;
    }

return angle;

} // end getAngle function

//**********************************************************************
// This function inputs an int into the string for opening file names

// see intoString in the combine.cpp program for fuction
```

APPENDIX E

SUBJECT DATA

BRmax

Sub/Cond #	Sub group	Vel $m \cdot s^{-1}$	Stride length cm	Stride Freq $Stride \cdot m^{-1}$	T ang GC deg	T ang TO deg	Δ T ang deg
S1C1	A	4.71	215.99	132.50	-6.85	-6.34	0.51
S2C1	A	5.36	235.18	138.49	-9.12	-4.66	4.46
S3C1	A	4.96	291.96	102.95	-5.49	2.17	7.66
S4C1	A	5.10	260.07	118.86	-5.34	1.87	7.21
S5C1	A	4.00	220.83	109.77	-12.95	-9.31	3.64
S6C1	A	4.91	246.48	121.11	-12.52	-13.15	0.63
S7C1	A	4.77	223.33	129.88	-14.26	-17.71	3.44
S8C1	A	5.15	269.47	115.87	4.92	5.51	0.58
S9C1	A	4.09	288.16	85.72	-12.71	-16.07	3.36
S10C1	A	4.85	234.62	125.70	-30.75	-25.96	4.79
S11C1	A	4.42	212.78	126.06	-31.43	-24.09	7.34
S12C1	A	4.31	187.56	139.62	-3.99	-7.36	3.37
S13C1	A	4.62	241.09	116.37	-10.08	-10.30	0.23
S14C1	A	4.61	241.82	115.39	-42.55	-38.35	4.20
S15C1	A	4.83	218.04	134.33	-12.89	-11.89	1.01
S21C1	E	5.46	241.79	137.23	-14.03	-13.42	0.61
S22C1	E	5.88	237.88	150.05	-12.21	-6.95	5.26
S23C1	E	5.72	236.46	146.96	-10.69	-8.01	2.67
S24C1	E	5.92	326.81	109.79	-7.98	-5.40	2.58
S25C1	E	5.39	259.81	126.38	-15.64	-11.14	4.50
S26C1	E	5.58	312.37	108.91	-23.33	-17.36	5.97
S27C1	E	5.08	234.23	131.45	-44.42	-42.65	1.77
S28C1	E	5.12	265.71	116.89	-24.99	-23.74	1.26
S29C1	E	5.42	322.76	101.69	-13.12	-9.96	3.16
S30C1	E	5.40	262.53	124.57	-28.38	-23.69	4.70
S31C1	E	4.94	225.74	132.89	-19.28	-18.32	0.96
S32C1	E	5.53	265.72	126.75	-13.52	-7.19	6.33
S33C1	E	5.65	235.60	145.99	-0.38	3.25	3.63
S34C1	E	5.12	255.92	121.24	-20.18	-17.05	3.13
S35C1	E	5.12	226.35	137.46	-29.88	-27.23	2.65

Sub - Subject, Cond - Condition
Vel - Velocity
Freq - Frequency
T ang GC - Trunk angle at ground contact
T ang TO - Trunk angle at toe-off
Δ T ang - change in trunk angle from ground contact to toe-off

BRmax

Sub/Cond #	Sub group	Hip ROM deg	Knee ROM deg	Ankle ROM deg	H vel TO $deg \cdot s^{-1}$	K vel TO $deg \cdot s^{-1}$	A vel TO $deg \cdot s^{-1}$
S1C1	A	34.06	71.11	38.96	285.32	82.80	607.13
S2C1	A	43.58	80.36	42.17	475.66	218.20	555.23
S3C1	A	47.23	77.30	42.23	197.32	162.85	566.74
S4C1	A	51.74	82.22	47.70	246.93	229.85	421.64
S5C1	A	59.90	110.76	40.11	201.89	126.44	605.99
S6C1	A	37.86	72.22	48.46	342.94	154.43	712.55
S7C1	A	41.55	90.73	54.14	290.75	112.16	809.15
S8C1	A	49.33	80.13	46.09	170.48	53.58	755.75
S9C1	A	38.68	72.10	53.36	172.42	109.81	649.40
S10C1	A	41.27	93.09	53.49	553.36	35.61	290.89
S11C1	A	25.28	83.08	50.36	512.32	127.82	722.49
S12C1	A	37.01	61.57	44.45	461.95	35.93	495.89
S13C1	A	46.86	62.45	39.40	244.90	-23.35	309.55
S14C1	A	31.55	85.44	54.76	370.39	24.76	682.16
S15C1	A	40.47	72.18	37.45	533.31	19.59	473.27
S21C1	E	29.63	88.33	45.48	639.00	15.50	666.78
S22C1	E	28.92	80.42	43.14	520.83	72.78	562.46
S23C1	E	29.88	68.79	39.24	349.47	121.74	449.24
S24C1	E	58.80	112.19	46.28	191.76	132.28	717.02
S25C1	E	45.93	103.97	46.33	423.66	155.94	746.34
S26C1	E	53.87	91.76	44.09	380.16	127.68	745.69
S27C1	E	52.63	83.13	47.56	355.32	71.18	584.71
S28C1	E	42.78	85.23	42.10	443.52	172.91	346.70
S29C1	E	60.02	101.40	43.79	324.56	154.47	426.94
S30C1	E	40.38	76.90	44.01	242.61	118.73	605.23
S31C1	E	30.77	75.40	38.65	423.97	27.74	359.33
S32C1	E	42.18	79.44	36.53	225.88	-30.50	547.07
S33C1	E	34.74	75.98	44.67	504.98	47.26	712.34
S34C1	E	45.34	84.64	45.26	179.80	74.83	677.88
S35C1	E	32.24	90.64	48.40	730.93	187.24	283.18

Sub - Subject
Cond - Condition
Vel - Velocity
ROM - Range of motion
TO - Toe-off
H - Hip, K - Knee, A - Ankle

BRmax

Sub/Cond #	Sub group	Δ height cm	F max V $m*s^{-1}$	H to A (GC) % leg len	H to A (TO) % leg len	ISL % leg len	Stance t ms	I Accel f % BW
S1C1	A	3.14	9.62	23.84	39.08	62.93	151.3	11.71
S2C1	A	2.66	11.24	27.25	46.10	73.35	142.3	30.06
S3C1	A	3.95	10.52	41.36	47.74	89.10	170.0	47.23
S4C1	A	4.31	10.56	31.77	48.52	80.28	179.5	0.00
S5C1	A	4.26	8.07	22.13	40.00	62.13	167.0	45.41
S6C1	A	3.21	10.17	26.79	43.10	69.89	152.0	6.80
S7C1	A	4.16	9.32	33.65	42.36	76.01	140.0	21.39
S8C1	A	3.15	10.52	36.61	33.49	70.09	157.3	36.78
S9C1	A	7.82	8.05	43.77	37.34	81.11	196.0	17.83
S10C1	A	3.51	9.90	14.23	47.99	62.23	131.0	34.90
S11C1	A	5.35	9.80	20.22	47.70	67.92	160.0	30.28
S12C1	A	5.02	8.87	30.62	40.00	70.61	153.7	10.71
S13C1	A	5.75	8.96	38.46	40.24	78.70	159.0	13.16
S14C1	A	5.25	10.16	18.50	49.21	67.70	188.3	0.00
S15C1	A	2.99	9.88	24.22	44.39	68.60	151.3	18.27
S21C1	E	2.81	11.28	19.33	46.52	65.85	129.7	42.99
S22C1	E	2.28	12.13	16.75	48.79	65.53	115.0	34.57
S23C1	E	2.95	11.41	17.66	44.82	62.48	138.7	18.60
S24C1	E	2.70	12.62	30.70	49.55	80.24	153.0	50.93
S25C1	E	3.02	10.70	10.46	43.38	53.85	138.0	56.53
S26C1	E	2.64	11.31	22.54	48.85	71.39	163.7	34.80
S27C1	E	4.02	10.78	7.63	54.32	61.95	130.7	10.81
S28C1	E	3.87	10.46	24.76	54.49	79.25	143.7	38.19
S29C1	E	3.04	11.38	30.11	48.28	78.39	146.0	72.46
S30C1	E	3.50	11.61	32.70	48.69	81.39	162.0	17.37
S31C1	E	2.83	10.39	24.14	44.00	68.14	140.7	59.98
S32C1	E	3.63	11.22	26.93	37.74	64.67	119.0	84.99
S33C1	E	2.93	11.56	16.67	51.40	68.07	115.0	60.36
S34C1	E	3.34	10.71	29.55	44.81	74.36	155.3	46.38
S35C1	E	3.20	11.35	21.05	60.92	81.97	139.3	50.81

Sub - Subject, Cond - Condition, Vel - Velocity
Δ height - change in vertical distance
H to A (GC) - Hip to ankle dist at GC, H to A (TO) - Hip to ankle dist toe-off
ISL - Intrinsic support length
Stance t - Stance time
I accel f - Initial acceleration force

BRmax

Sub/Cond #	Sub group	Imp peak BW	Imp t % stance t	Imp slope BW/s	Resultant active peak BW	Active t % stance t	F brake f % BW
S1C1	A	1.304	12.9	103	2.507	47.2	-2.92
S2C1	A	2.011	10.1	318	2.505	48.9	-1.81
S3C1	A	1.531	7.3	211	2.928	62.7	-0.95
S4C1	A	1.072	12.2	99	2.326	50.8	-1.14
S5C1	A	1.137	7.4	160	2.689	50.3	-1.97
S6C1	A	1.171	11.3	122	2.509	41.7	-3.90
S7C1	A	1.345	12.6	183	2.780	53.9	-9.78
S8C1	A	1.500	9.3	176	2.359	45.8	-3.17
S9C1	A	1.328	9.6	180	3.426	40.6	-1.05
S10C1	A	1.809	11.5	176	3.426	48.2	-4.56
S11C1	A	1.831	8.9	299	2.525	36.9	-6.23
S12C1	A	1.411	10.8	166	2.239	48.8	-2.44
S13C1	A	1.122	16.0	97	2.392	45.5	-1.25
S14C1	A	1.143	15.4	122	2.367	43.5	-7.10
S15C1	A	1.663	11.5	210	2.475	49.8	0.00
S21C1	E	1.899	9.3	229	2.718	56.8	-1.79
S22C1	E	1.965	9.8	307	2.748	46.9	-1.46
S23C1	E	1.320	10.4	139	2.682	46.8	-2.94
S24C1	E	1.486	7.2	237	2.920	58.1	-5.76
S25C1	E	2.937	7.3	580	2.899	43.1	-1.94
S26C1	E	1.804	11.7	259	2.839	51.9	-1.71
S27C1	E	0.818	10.2	102	3.108	52.3	-0.74
S28C1	E	2.261	8.8	423	3.034	46.8	-2.13
S29C1	E	1.876	7.5	329	2.853	43.2	-2.02
S30C1	E	1.082	8.8	99	2.975	60.7	-4.41
S31C1	E	1.971	9.0	282	3.065	54.3	-4.25
S32C1	E	2.378	9.2	421	4.181	56.3	-2.38
S33C1	E	2.10	9.6	394	3.68	48.8	-1.62
S34C1	E	1.172	6.7	173	2.645	48.2	-3.44
S35C1	E	2.697	6.5	455	2.695	35.2	-0.16

Sub - Subject, Cond - Condition, Vel - Velocity
Imp peak - Impact peak, BW - Body weight
Imp t - Impact time, % stance t - Percent stance time
Active t - Time to resultant active peak
F brake f - Final braking force

BR$_{80}$

Sub/Cond #	Sub group	Vel $m \cdot s^{-1}$	Stride length cm	Stride Freq $Stride \cdot m^{-1}$	T ang GC deg	T ang TO deg	Δ T ang deg
S1C2	A	3.92	212.22	111.87	-5.52	-4.86	0.66
S2C2	A	4.56	225.89	122.47	-2.85	0.63	3.48
S3C2	A	4.46	254.98	105.90	-2.48	3.93	6.41
S4C2	A	4.30	228.05	114.54	-5.72	-0.90	4.81
S5C2	A	3.49	196.62	107.50	-6.54	-6.99	0.45
S6C2	A	4.38	265.24	100.28	-6.37	-5.72	0.65
S7C2	A	4.19	229.85	110.53	-2.86	-7.58	4.72
S8C2	A	4.35	240.99	109.67	0.89	0.14	0.75
S9C2	A	3.76	269.70	84.40	-8.89	-9.97	1.08
S10C2	A	4.04	242.61	100.87	-12.30	-10.85	1.45
S11C2	A	3.76	186.31	122.39	-21.43	-15.09	6.34
S12C2	A	3.97	204.49	117.65	1.90	-0.28	2.18
S13C2	A	3.78	211.95	108.13	-3.85	-6.81	2.95
S14C2	A	3.79	252.18	90.87	-29.13	-25.07	4.07
S15C2	A	4.17	199.36	126.76	-13.35	-10.52	2.83
S21C2	E	4.68	243.63	116.62	-7.49	-5.32	2.17
S22C2	E	5.06	231.05	132.89	-10.07	-7.56	2.50
S23C2	E	4.91	234.39	127.07	-9.97	-8.76	1.21
S24C2	E	4.51	279.56	97.63	-7.93	-6.05	1.89
S25C2	E	4.67	300.46	94.04	-14.39	-10.02	4.37
S26C2	E	4.81	313.29	92.91	-19.34	-12.59	6.76
S27C2	E	4.09	242.49	102.07	-46.72	-44.37	2.35
S28C2	E	4.28	275.44	94.01	-11.68	-8.43	3.25
S29C2	E	4.64	295.18	95.03	-12.11	-8.60	3.51
S30C2	E	4.65	286.33	98.20	-14.51	-11.65	2.85
S31C2	E	4.38	224.85	118.17	-15.19	-13.39	1.79
S32C2	E	5.22	297.42	106.19	-10.59	-5.09	5.51
S33C2	E	4.80	214.12	136.37	3.90	3.18	0.72
S34C2	E	4.41	242.17	110.44	-18.09	-17.82	0.28
S35C2	E	4.31	220.65	118.99	-30.81	-30.48	0.34

Sub - Subject, Cond - Condition
Vel - Velocity
Freq - Frequency
T ang GC - Trunk angle at ground contact
T ang TO - Trunk angle at toe-off
Δ T ang - change in trunk angle from ground contact to toe-off

BR$_{80}$

Sub/Cond #	Sub group	Hip ROM deg	Knee ROM deg	Ankle ROM deg	H vel TO deg•s^{-1}	K vel TO deg•s^{-1}	A vel TO deg•s^{-1}
S1C2	A	32.91	71.48	38.18	180.78	116.18	533.73
S2C2	A	36.82	71.30	39.97	330.54	82.88	500.15
S3C2	A	44.27	93.64	46.13	177.47	193.80	653.68
S4C2	A	41.27	74.99	46.07	33.78	148.74	451.02
S5C2	A	50.52	98.61	35.33	156.32	116.02	551.93
S6C2	A	42.87	81.15	50.80	154.82	165.90	651.42
S7C2	A	47.75	92.51	54.90	153.43	79.14	693.45
S8C2	A	40.19	71.20	42.48	61.58	56.58	622.49
S9C2	A	40.62	76.13	53.50	79.58	118.10	608.80
S10C2	A	39.82	77.29	53.04	223.58	76.40	602.93
S11C2	A	28.39	66.16	43.66	319.27	52.33	523.12
S12C2	A	38.34	62.22	47.31	374.16	21.77	524.55
S13C2	A	41.78	56.85	37.45	148.36	-49.60	251.48
S14C2	A	30.92	87.12	56.39	235.40	0.70	694.28
S15C2	A	25.59	64.22	34.02	350.27	104.61	252.35
S21C2	E	30.94	74.80	51.90	387.46	71.56	553.38
S22C2	E	35.54	75.78	34.68	246.14	69.94	400.28
S23C2	E	31.21	75.40	38.82	374.88	102.77	356.98
S24C2	E	47.51	113.73	46.60	126.97	118.44	580.19
S25C2	E	47.85	115.48	45.73	144.36	192.71	777.73
S26C2	E	46.22	85.68	42.53	118.05	146.31	579.07
S27C2	E	37.73	77.97	60.09	264.97	135.93	259.03
S28C2	E	43.79	80.11	42.77	117.99	153.97	453.24
S29C2	E	51.89	87.76	43.55	223.03	86.39	260.80
S30C2	E	45.48	78.92	48.87	25.88	104.01	612.01
S31C2	E	28.27	65.90	34.98	310.88	13.59	342.49
S32C2	E	47.83	63.49	32.55	55.92	-8.97	514.89
S33C2	E	28.69	73.81	44.76	412.56	188.72	639.95
S34C2	E	39.36	84.95	39.86	112.92	123.86	568.17
S35C2	E	28.99	93.81	58.05	601.50	7.81	123.26

Sub - Subject
Cond - Condition
Vel - Velocity
ROM - Range of motion
TO - Toe-off
H - Hip, K - Knee, A - Ankle

BR_{80}

Sub/Cond #	Sub group	Δ height cm	F max V $m \cdot s^{-1}$	H to A (GC) % leg len	H to A (TO) % leg len	ISL % leg len	Stance t ms	I Accel f % BW
S1C2	A	3.84	7.79	22.43	39.43	61.86	178.7	5.40
S2C2	A	3.81	9.29	33.68	40.09	73.77	162.3	23.03
S3C2	A	4.06	9.29	25.53	46.60	72.13	168.3	31.15
S4C2	A	5.49	8.85	26.65	47.49	74.14	196.0	1.03
S5C2	A	4.65	7.43	24.20	33.09	57.29	187.7	11.68
S6C2	A	5.29	9.13	30.31	45.57	75.88	181.3	15.17
S7C2	A	5.70	8.16	35.36	45.26	80.62	171.0	7.73
S8C2	A	4.12	8.91	32.32	31.47	63.80	174.7	31.57
S9C2	A	6.38	7.18	34.69	41.30	75.99	211.7	4.86
S10C2	A	5.57	8.11	24.14	43.12	67.26	174.0	9.16
S11C2	A	4.73	8.01	10.42	47.78	58.20	176.7	8.27
S12C2	A	5.48	8.07	31.81	40.92	72.73	177.7	20.39
S13C2	A	5.50	7.65	40.90	39.30	80.20	195.3	3.75
S14C2	A	7.50	8.17	27.10	45.63	72.73	246.0	1.79
S15C2	A	3.51	9.12	21.14	42.97	64.11	173.0	30.04
S21C2	E	4.56	9.70	20.54	45.49	66.03	152.3	13.41
S22C2	E	2.42	10.13	24.80	42.79	67.59	130.7	34.59
S23C2	E	3.42	9.69	30.54	44.79	75.33	165.5	6.52
S24C2	E	4.97	9.86	35.19	44.10	79.29	194.0	22.86
S25C2	E	4.83	9.86	20.14	41.36	61.50	171.3	31.66
S26C2	E	4.57	9.77	35.10	48.71	83.81	200.3	6.00
S27C2	E	4.65	8.92	23.46	56.74	80.20	204.0	6.65
S28C2	E	5.17	8.05	29.62	46.81	76.43	181.0	3.07
S29C2	E	4.00	9.55	33.14	51.16	84.30	172.7	43.01
S30C2	E	4.88	9.96	43.54	49.92	93.46	215.0	9.64
S31C2	E	3.76	9.37	25.60	42.55	68.15	160.7	47.10
S32C2	E	4.48	11.00	36.95	31.69	68.64	135.7	57.42
S33C2	E	4.71	9.82	20.61	54.30	74.91	138.7	34.93
S34C2	E	3.41	9.28	35.94	45.21	81.15	186.3	27.26
S35C2	E	6.18	8.52	10.63	60.43	71.05	148.7	51.55

Sub - Subject, Cond - Condition, Vel - Velocity
Δ height - change in vertical distance
H to A (GC) - Hip to ankle dist at GC, H to A (TO) - Hip to ankle dist toe-off
ISL - Intrinsic support length
Stance t - Stance time
I accel f - Initial acceleration force

BR$_{80}$

Sub/Cond #	Sub group	Imp peak BW	Imp t % stance t	Imp slope BW/s	Resultant active peak BW	Active t % stance t	F brake f % BW
S1C2	A	0.848	15.3	63	2.506	49.4	-2.56
S2C2	A	1.313	10.4	142	2.457	47.6	-1.28
S3C2	A	1.312	7.9	157	3.002	56.2	-0.31
S4C2	A	0.916	16.2	62	2.156	53.4	-1.62
S5C2	A	0.48	10.7	55	2.39	48.0	-2.19
S6C2	A	0.920	11.4	85	2.529	48.0	-3.80
S7C2	A	0.988	16.7	91	2.818	52.1	-5.31
S8C2	A	1.492	8.8	169	2.628	50.0	-3.48
S9C2	A	0.888	11.3	77	2.935	41.9	-0.52
S10C2	A	1.051	12.6	86	3.180	50.9	-3.71
S11C2	A	1.206	12.0	144	2.235	42.3	-2.14
S12C2	A	1.071	11.5	82	2.246	47.1	-1.97
S13C2	A	0.274	5.6	41	2.255	51.0	-1.30
S14C2	A	0.779	16.5	39	2.082	44.8	-6.37
S15C2	A	1.329	7.8	211	2.601	45.9	-0.63
S21C2	E	1.220	10.4	160	3.023	48.5	-0.43
S22C2	E	1.464	10.4	211	3.346	58.6	0.00
S23C2	E	1.34	10.42	98	2.370	39.3	-3.72
S24C2	E	0.745	7.3	103	2.922	53.0	-5.56
S25C2	E	1.463	6.3	194	3.048	56.6	-3.41
S26C2	E	0.651	11.8	116	2.804	56.6	-1.33
S27C2	E	0.465	4.6	86	2.538	55.8	-6.46
S28C2	E	1.023	12.9	122	2.960	55.2	0.00
S29C2	E	1.229	7.7	225	3.038	53.9	-1.76
S30C2	E	0.520	6.2	61	2.526	53.9	-2.95
S31C2	E	1.551	9.5	183	2.397	47.8	-3.40
S32C2	E	1.632	7.9	224	3.532	61.4	-0.48
S33C2	E	1.52	10.6	200	2.76	47.0	-0.74
S34C2	E	0.736	6.6	102	2.240	49.9	-2.63
S35C2	E	2.28	5.4	441	2.75	29.6	-2.02

Sub - Subject, Cond - Condition, Vel - Velocity
Imp peak - Impact peak, BW - Body weight
Imp t - Impact time, % stance t - Percent stance time
Active t - Time to resultant active peak
F brake f - Final braking force

BR60

Sub/Cond #	Sub group	Vel $m \cdot s^{-1}$	Stride length cm	Stride Freq $Stride \cdot m^{-1}$	T ang GC deg	T ang TO deg	Δ T ang deg
S1C3	A	2.90	179.95	97.38	-6.18	-4.18	2.00
S2C3	A	3.34	205.28	98.64	-0.61	1.32	1.93
S3C3	A	3.40	226.38	90.81	-2.74	3.32	6.06
S4C3	A	3.33	228.16	88.62	-5.77	-3.43	2.34
S5C3	A	2.74	182.68	90.76	-4.59	-4.05	0.54
S6C3	A	3.31	248.34	80.58	-4.25	-1.98	2.27
S7C3	A	3.09	215.38	86.75	0.25	-1.68	1.93
S8C3	A	3.22	192.54	101.27	1.84	4.37	2.53
S9C3	A	2.99	237.26	76.12	-6.96	-7.41	0.44
S10C3	A	4.15	247.94	100.33	-9.91	-10.00	0.09
S11C3	A	2.96	177.20	101.32	-10.64	-6.17	4.47
S11C3	A	2.97	183.86	97.69	0.60	0.12	0.48
S13C3	A	3.18	224.06	85.86	-2.17	-4.52	2.35
S14C3	A	3.07	239.88	77.28	-24.05	-22.44	1.62
S15C3	A	3.09	184.77	101.41	-5.43	-4.14	1.29
S21C3	E	3.30	214.85	93.04	-3.19	-1.69	1.50
S22C3	E	4.01	223.71	109.04	-7.02	-5.00	2.02
S23C3	E	3.70	197.35	114.00	-9.95	-6.08	3.87
S24C3	E	3.68	243.64	91.39	-4.52	-1.41	3.11
S25C3	E	3.55	256.94	83.40	-12.31	-8.42	3.89
S26C3	E	3.65	272.40	80.94	-22.53	-11.26	11.28
S27C3	E	3.35	186.86	108.44	-44.70	-42.66	2.04
S28C3	E	3.37	234.61	86.83	-8.24	-6.18	2.06
S29C3	E	3.50	250.24	84.79	-5.99	-3.15	2.83
S30C3	E	3.38	229.97	88.91	-14.82	-13.99	0.83
S31C3	E	3.36	208.01	98.14	-8.15	-7.02	1.13
S32C3	E	4.33	248.79	105.30	-14.01	-7.48	6.53
S33C3	E	3.55	177.00	121.67	7.40	9.86	2.46
S34C3	E	3.15	216.89	87.87	-6.04	-5.01	1.03
S35C3	E	3.39	194.34	105.61	-33.32	-31.06	2.26

Sub - Subject, Cond - Condition
Vel - Velocity
Freq - Frequency
T ang GC - Trunk angle at ground contact
T ang TO - Trunk angle at toe-off
Δ T ang - change in trunk angle from ground contact to toe-off

BR$_{60}$

Sub/Cond #	Sub group	Hip ROM deg	Knee ROM deg	Ankle ROM deg	H vel TO $deg \cdot s^{-1}$	K vel TO $deg \cdot s^{-1}$	A vel TO $deg \cdot s^{-1}$
S1C3	A	30.86	72.48	41.75	85.81	103.10	541.33
S2C3	A	37.25	69.83	41.67	233.07	40.66	416.79
S3C3	A	43.28	94.85	44.85	50.85	155.99	613.96
S4C3	A	34.49	70.99	49.79	44.44	121.19	399.39
S5C3	A	42.80	90.25	46.75	60.98	37.00	511.53
S6C3	A	48.77	88.53	50.91	17.92	153.70	631.06
S7C3	A	53.61	92.40	56.65	17.36	56.55	606.87
S8C3	A	45.23	70.96	39.15	-140.24	87.14	477.98
S9C3	A	42.69	79.60	49.53	-46.77	102.19	588.90
S10C3	A	44.04	74.25	48.68	79.39	84.68	461.36
S11C3	A	27.92	59.97	40.64	128.96	-11.90	499.94
S11C3	A	30.13	58.23	45.35	226.64	-2.04	434.66
S13C3	A	42.55	58.01	45.67	157.24	-9.92	310.18
S14C3	A	40.01	93.93	56.94	152.67	18.56	587.63
S15C3	A	27.63	67.47	40.18	235.68	75.75	382.87
S21C3	E	31.79	67.72	50.34	189.24	54.21	457.90
S22C3	E	36.42	73.10	33.91	-1.84	98.50	341.91
S23C3	E	29.42	66.38	36.87	289.84	0.81	328.62
S24C3	E	44.80	119.69	45.49	110.45	158.90	547.45
S25C3	E	41.56	106.85	48.66	-2.91	129.82	644.53
S26C3	E	50.80	89.28	30.92	66.62	176.19	-311.16
S27C3	E	27.67	74.18	51.06	262.56	52.33	363.18
S28C3	E	38.38	84.16	42.23	109.28	132.69	405.03
S29C3	E	46.23	81.09	39.06	134.69	68.91	278.71
S30C3	E	40.00	71.30	45.87	1.31	70.76	545.21
S31C3	E	35.89	70.28	40.35	193.41	15.23	298.96
S32C3	E	47.91	66.88	32.73	78.30	7.58	433.88
S33C3	E	32.03	81.68	47.98	304.79	210.64	540.70
S34C3	E	44.00	83.32	40.55	135.62	99.57	477.55
S35C3	E	28.39	89.70	45.38	403.55	106.09	192.24

Sub - Subject
Cond - Condition
Vel - Velocity
ROM - Range of motion
TO - Toe-off
H - Hip, K - Knee, A - Ankle

BR60

Sub/Cond #	Sub group	Δ height cm	F max V $m*s^{-1}$	H to A (GC) % leg len	H to A (TO) % leg len	ISL % leg len	Stance t ms	I Accel f % BW
S1C3	A	5.02	5.80	16.38	37.49	53.87	219.0	0.75
S2C3	A	4.80	7.05	34.96	41.89	76.85	235.3	7.69
S3C3	A	6.61	7.48	24.62	45.71	70.34	220.3	29.84
S4C3	A	8.05	6.85	28.62	44.45	73.07	234.0	0.65
S5C3	A	5.23	5.78	21.19	36.27	57.45	252.0	6.73
S6C3	A	7.04	7.21	31.96	46.38	78.35	251.7	22.35
S7C3	A	8.44	6.13	41.95	45.19	87.14	262.0	9.25
S8C3	A	4.04	7.28	20.49	34.88	55.37	264.7	17.72
S9C3	A	7.60	5.88	29.83	40.47	70.29	258.0	5.70
S10C3	A	7.75	7.21	24.65	46.16	70.81	215.0	15.85
S11C3	A	5.25	6.42	11.34	44.48	55.81	220.0	4.24
S11C3	A	6.64	6.18	25.38	39.26	64.64	228.0	5.49
S13C3	A	6.28	6.80	45.71	43.69	89.40	271.7	0.00
S14C3	A	8.73	6.62	33.59	45.63	79.22	325.0	3.99
S15C3	A	6.58	6.93	23.29	46.29	69.58	230.7	30.61
S21C3	E	6.17	7.17	25.22	42.32	67.54	222.0	0.89
S22C3	E	3.73	8.01	21.69	39.64	61.34	153.3	48.32
S23C3	E	3.74	7.70	27.21	43.92	71.14	214.7	0.00
S24C3	E	6.15	8.38	23.27	45.02	68.29	217.3	38.25
S25C3	E	6.58	7.88	22.95	38.37	61.32	226.7	15.07
S26C3	E	6.00	8.21	29.44	63.24	92.68	312.0	0.00
S27C3	E	4.01	7.85	9.15	55.07	64.23	219.3	0.00
S28C3	E	7.09	6.62	24.35	47.86	72.22	217.3	4.90
S29C3	E	6.02	7.56	30.89	46.04	76.94	208.0	39.11
S30C3	E	6.98	7.72	43.93	43.91	87.84	264.0	9.42
S31C3	E	5.48	7.79	29.02	47.01	76.03	220.3	35.32
S32C3	E	5.69	10.27	30.37	36.84	67.22	158.7	74.95
S33C3	E	5.99	7.65	11.33	56.51	67.84	169.3	26.78
S34C3	E	5.69	6.81	38.37	43.62	82.00	269.7	17.04
S35C3	E	4.79	7.12	9.73	64.16	73.89	198.7	8.83

Sub - Subject, Cond - Condition, Vel - Velocity
Δ height - change in vertical distance
H to A (GC) - Hip to ankle dist at GC, H to A (TO) - Hip to ankle dist toe-off
ISL - Intrinsic support length
Stance t - Stance time
I accel f - Initial acceleration force

BR$_{60}$

Sub/Cond #	Sub group	Imp peak BW	Imp t % stance t	Imp slope BW/s	Resultant active peak BW	Active t % stance t	F brake f % BW
S1C3	A	0.104	4.1	35	2.407	52.5	-3.61
S2C3	A	0.465	12.6	38	2.067	58.6	-1.09
S3C3	A	0.696	7.2	102	2.654	63.8	-0.59
S4C3	A	0.724	13.1	48	2.487	58.1	-2.95
S5C3	A	0.287	10.8	28	2.145	46.4	-2.15
S6C3	A	0.551	6.6	59	2.237	61.5	-2.01
S7C3	A	0.385	11.9	52	2.098	45.7	-3.03
S8C3	A	0.412	6.2	43	2.143	55.3	-2.73
S9C3	A	0.638	13.6	44	2.494	52.6	-0.99
S10C3	A	0.715	10.9	62	2.538	60.3	-2.72
S11C3	A	0.716	15.9	45	2.302	58.6	-0.22
S11C3	A	0.136	3.8	41	2.248	54.0	-2.13
S13C3	A	0.097	3.5	20	1.888	51.8	-1.61
S14C3	A	0.256	7.6	30	2.019	68.1	-2.88
S15C3	A	1.155	8.0	134	2.356	48.4	-1.24
S21C3	E	0.657	15.1	39	2.521	50.9	-1.87
S22C3	E	1.228	8.9	179	2.451	58.2	-0.14
S23C3	E	0.414	8.959	33	1.638	62.1	-2.57
S24C3	E	0.89	6.0	111	2.69	49.5	-3.79
S25C3	E	0.550	8.1	54	2.767	62.8	-4.18
S26C3	E	0.490	8.9	58	2.408	57.0	-2.06
S27C3	E	0.280	10.5	28	2.223	66.6	-1.08
S28C3	E	0.764	11.3	61	2.663	60.1	-0.14
S29C3	E	0.923	7.4	122	2.805	54.9	-2.05
S30C3	E	0.364	4.9	35	2.478	61.3	-4.42
S31C3	E	0.766	9.4	72	2.234	57.7	-3.41
S32C3	E	1.556	8.8	222	3.068	60.7	-5.04
S33C3	E	0.75	7.8	84	2.52	49.0	-0.41
S34C3	E	0.420	3.5	58	2.041	63.2	-1.37
S35C3	E	1.007	8.2	123	1.994	53.5	0.00

Sub - Subject, Cond - Condition, Vel - Velocity
Imp peak - Impact peak, BW - Body weight
Imp t - Impact time, % stance t - Percent stance time
Active t - Time to resultant active peak
F brake f - Final braking force

FRmax

Sub/Cond #	Sub group	Vel $m \cdot s^{-1}$	Stride length cm	Stride Freq $Stride \cdot m^{-1}$	T ang GC deg	T ang TO deg	Δ T ang deg
S1C4	A	6.96	390.83	107.82	19.13	14.02	5.11
S2C4	A	7.22	342.70	127.67	6.94	13.59	6.65
S3C4	A	6.32	392.72	97.17	4.46	9.20	4.74
S4C4	A	7.08	410.30	104.59	21.45	21.25	0.20
S5C4	A	6.38	355.18	108.78	13.33	17.54	4.21
S6C4	A	6.99	426.30	99.21	14.80	18.77	3.96
S7C4	A	7.07	361.51	118.55	18.15	23.09	4.94
S8C4	A	6.98	401.04	105.36	13.43	14.63	1.19
S9C4	A	6.31	433.08	88.19	11.28	10.90	0.38
S10C4	A	7.52	377.27	120.84	16.92	17.84	0.92
S11C4	A	7.31	440.73	100.34	16.43	19.19	2.76
S11C4	A	6.60	324.60	123.30	21.09	17.52	3.56
S13C4	A	6.00	383.13	94.74	6.40	9.94	3.54
S14C4	A	6.98	401.25	105.33	11.56	15.51	3.95
S15C4	A	6.44	385.71	100.87	24.45	28.48	4.03
S21C4	E	7.59	384.21	119.89	18.15	17.39	0.77
S22C4	E	7.99	424.34	114.04	24.95	18.49	6.46
S23C4	E	7.22	411.02	106.19	22.19	20.51	1.68
S24C4	E	8.16	376.71	131.74	16.69	14.12	2.57
S25C4	E	7.04	405.84	105.04	20.69	22.71	2.02
S26C4	E	7.87	443.26	107.46	13.20	11.89	1.31
S27C4	E	8.27	408.68	122.63	20.13	18.53	1.60
S28C4	E	7.25	382.68	114.69	23.91	19.86	4.05
S29C4	E	7.42	428.63	104.68	12.51	9.78	2.73
S30C4	E	7.80	366.41	129.24	26.43	25.34	1.09
S31C4	E	7.44	418.85	107.58	18.50	15.83	2.67
S32C4	E	7.92	371.96	129.06	14.63	18.65	4.02
S33C4	E	8.03	398.85	122.04	21.12	20.69	0.43
S34C4	E	7.24	404.87	108.22	20.63	14.58	6.05
S35C4	E	8.50	407.56	126.32	19.55	17.74	1.81

Sub - Subject, Cond - Condition
Vel - Velocity
Freq - Frequency
T ang GC - Trunk angle at ground contact
T ang TO - Trunk angle at toe-off
Δ T ang - change in trunk angle from ground contact to toe-off

FRmax

Sub/Cond #	Sub group	Hip ROM deg	Knee ROM deg	Ankle ROM deg	H vel TO $deg \cdot s^{-1}$	K vel TO $deg \cdot s^{-1}$	A vel TO $deg \cdot s^{-1}$
S1C4	A	68.28	140.77	52.58	-125.59	798.36	1139.83
S2C4	A	61.69	87.71	43.81	-25.20	607.31	465.62
S3C4	A	59.09	113.30	49.06	-162.80	574.12	1028.48
S4C4	A	75.82	131.38	48.41	-44.17	525.53	702.40
S5C4	A	76.90	126.21	47.77	55.49	616.06	812.18
S6C4	A	72.14	114.42	50.89	-25.70	704.22	956.15
S7C4	A	73.58	119.86	71.78	-238.47	716.58	1013.73
S8C4	A	58.36	133.09	65.29	-54.36	872.38	702.32
S9C4	A	70.27	114.71	56.72	-170.72	317.19	791.63
S10C4	A	72.86	114.41	47.59	14.88	541.40	762.84
S11C4	A	67.04	141.63	57.22	3.97	748.54	1147.66
S11C4	A	71.07	96.84	45.67	-10.51	399.16	745.60
S13C4	A	63.12	140.17	56.65	-271.00	304.09	849.82
S14C4	A	72.71	109.89	53.59	109.32	490.94	1062.38
S15C4	A	62.58	123.01	34.14	-24.64	477.54	757.54
S21C4	E	77.50	124.76	54.14	291.92	504.97	760.61
S22C4	E	69.62	128.78	51.63	-96.59	754.31	1072.59
S23C4	E	68.15	113.47	45.26	12.92	581.78	809.11
S24C4	E	71.09	110.52	62.96	-84.75	761.06	1001.11
S25C4	E	70.67	126.48	44.51	-103.87	600.06	400.34
S26C4	E	75.87	114.25	56.86	-16.78	482.59	866.59
S27C4	E	68.65	100.89	56.24	-147.63	659.45	1059.08
S28C4	E	73.84	107.43	51.27	-274.41	583.39	1163.54
S29C4	E	68.76	115.47	52.88	-171.49	689.42	1060.36
S30C4	E	69.83	87.15	48.10	-31.64	544.85	952.31
S31C4	E	67.24	117.91	40.97	-172.68	514.80	526.34
S32C4	E	65.86	101.41	32.41	184.99	813.49	787.81
S33C4	E	67.18	139.19	74.34	-26.57	741.89	982.18
S34C4	E	67.90	109.43	39.12	74.04	682.96	690.11
S35C4	E	70.15	114.08	50.76	-40.18	636.79	866.58

Sub - Subject
Cond - Condition
Vel - Velocity
ROM - Range of motion
TO - Toe-off
H - Hip, K - Knee, A - Ankle

FRmax

Sub/Cond #	Sub group	Δ height cm	F max V m*s-1	H to A (GC) % leg len	H to A (TO) % leg len	ISL % leg len	Stance t ms	I Accel f % BW
S1C4	A	1.79	13.37	38.72	49.01	87.73	139.7	0.00
S2C4	A	2.51	12.35	27.98	35.63	63.61	138.0	0.00
S3C4	A	2.98	10.31	43.34	50.78	94.12	157.0	12.63
S4C4	A	2.80	14.07	47.92	63.07	110.99	157.3	0.00
S5C4	A	3.23	11.43	40.29	56.93	97.22	153.0	0.00
S6C4	A	1.65	11.35	46.37	60.04	106.41	164.7	0.00
S7C4	A	2.72	14.19	45.10	58.38	103.48	141.7	0.00
S8C4	A	2.97	14.22	35.79	45.68	81.47	140.0	0.00
S9C4	A	3.94	10.51	40.09	60.49	100.58	173.0	0.00
S10C4	A	1.59	12.97	39.61	64.68	104.29	146.3	0.00
S11C4	A	1.62	12.84	44.34	52.43	96.77	145.3	0.00
S11C4	A	2.66	11.01	38.78	65.09	103.87	153.3	0.00
S13C4	A	1.89	9.78	40.89	51.95	92.84	144.7	0.00
S14C4	A	2.11	11.69	39.56	66.05	105.61	187.0	0.00
S15C4	A	1.47	10.67	51.18	36.35	87.53	153.7	13.28
S21C4	E	2.35	13.45	30.38	63.30	93.68	131.7	0.00
S22C4	E	2.57	13.39	33.10	50.73	83.83	115.0	0.00
S23C4	E	2.73	11.76	41.78	53.36	95.13	141.7	0.00
S24C4	E	2.77	14.46	41.63	61.59	103.23	141.3	0.00
S25C4	E	1.96	12.34	34.23	25.87	60.10	145.3	0.00
S26C4	E	5.27	14.02	32.57	58.65	91.22	153.0	0.00
S27C4	E	3.19	13.37	43.03	55.72	98.75	127.3	0.00
S28C4	E	2.89	11.62	44.60	55.76	100.35	146.0	0.00
S29C4	E	1.43	11.87	48.48	48.14	96.62	143.7	3.84
S30C4	E	2.38	12.48	41.36	62.63	103.99	147.0	0.00
S31C4	E	1.86	12.55	48.70	57.15	105.85	141.7	0.00
S32C4	E	2.95	13.32	33.78	59.25	93.03	123.7	0.00
S33C4	E	4.73	14.36	36.43	65.55	101.98	110.7	1.14
S34C4	E	2.51	11.93	38.28	55.52	93.80	130.0	0.00
S35C4	E	2.83	12.92	33.35	44.84	78.19	107.3	0.00

Sub - Subject, Cond - Condition, Vel - Velocity
Δ height - change in vertical distance
H to A (GC) - Hip to ankle dist at GC, H to A (TO) - Hip to ankle dist toe-off
ISL - Intrinsic support length
Stance t - Stance time
I accel f - Initial acceleration force

FRmax

Sub/Cond #	Sub group	Imp peak BW	Imp t % stance t	Imp slope BW/s	Resultant active peak BW	Active t % stance t	F brake f % BW
S1C4	A	2.301	10.7	338	3.079	46.1	0.00
S2C4	A	1.778	5.8	390	2.627	37.0	0.00
S3C4	A	2.797	12.7	323	2.957	43.6	0.00
S4C4	A	3.730	10.3	454	2.472	48.2	0.00
S5C4	A	1.561	9.6	195	2.859	44.4	0.00
S6C4	A	2.810	9.3	423	2.659	49.3	0.00
S7C4	A	1.453	10.8	222	2.643	38.5	0.00
S8C4	A	2.443	12.2	222	3.060	42.6	0.00
S9C4	A	1.818	12.8	308	2.636	44.6	0.00
S10C4	A	1.807	8.0	316	2.721	40.4	0.00
S11C4	A	3.296	8.9	577	2.798	45.6	0.00
S11C4	A	1.307	10.4	228	2.420	42.3	0.00
S13C4	A	1.084	5.5	179	3.323	44.0	0.00
S14C4	A	1.695	8.1	175	2.347	45.3	0.00
S15C4	A	3.011	12.8	315	2.443	47.5	0.00
S21C4	E	2.608	11.9	277	2.653	39.1	0.00
S22C4	E	3.305	13.4	344	3.194	29.9	0.00
S23C4	E	3.520	11.1	545	2.701	42.3	0.00
S24C4	E	1.585	8.5	221	2.534	43.4	0.00
S25C4	E	1.509	9.2	158	2.931	44.1	0.00
S26C4	E	1.426	14.0	238	3.451	45.2	-0.76
S27C4	E	2.790	9.7	316	2.448	40.2	0.00
S28C4	E	0.984	6.9	136	2.938	46.8	0.00
S29C4	E	2.601	17.1	305	2.934	45.6	0.00
S30C4	E	1.800	12.7	160	2.446	44.2	0.00
S31C4	E	3.671	12.7	494	2.847	47.3	0.00
S32C4	E	1.925	10.2	272	3.018	39.0	0.00
S33C4	E	1.43	5.4	251	3.10	38.9	0.00
S34C4	E	3.457	17.7	328	3.049	36.4	0.00
S35C4	E	2.233	11.8	245	3.286	32.3	0.00

Sub - Subject, Cond - Condition, Vel - Velocity
Imp peak - Impact peak, BW - Body weight
Imp t - Impact time, % stance t - Percent stance time
Active t - Time to resultant active peak
F brake f - Final braking force

FRequal

Sub/Cond #	Sub group	Vel $m \cdot s^{-1}$	Stride length cm	Stride Freq $Stride \cdot m^{-1}$	T ang GC deg	T ang TO deg	Δ T ang deg
S1C5	A	4.63	334.36	83.54	11.16	9.57	1.59
S2C5	A	5.47	350.37	94.27	0.35	6.30	5.95
S3C5	A	5.52	406.12	82.01	1.00	10.71	9.70
S4C5	A	4.97	383.56	78.13	19.88	22.14	2.26
S5C5	A	4.21	304.98	83.43	8.92	12.63	3.71
S6C5	A	5.30	378.19	84.61	8.51	12.69	4.18
S7C5	A	4.97	351.94	85.33	13.12	19.57	6.45
S8C5	A	5.30	381.06	83.94	4.30	8.46	4.16
S9C5	A	4.49	336.32	81.57	8.53	11.79	3.25
S10C5	A	4.88	363.39	88.67	10.63	10.97	0.35
S11C5	A	4.01	391.99	74.87	6.10	10.78	4.68
S11C5	A	4.03	324.99	88.68	12.51	12.66	0.15
S13C5	A	4.83	352.49	82.79	6.91	12.83	5.92
S14C5	A	4.76	378.81	75.79	9.41	14.99	5.58
S15C5	A	4.62	366.36	84.91	15.60	24.80	9.19
S21C5	E	5.04	383.89	92.40	11.49	14.97	3.48
S22C5	E	5.66	414.45	106.95	24.32	16.90	7.42
S23C5	E	5.63	401.51	91.65	16.79	17.62	0.82
S24C5	E	5.74	339.32	102.31	16.20	12.70	3.50
S25C5	E	5.11	397.54	92.87	18.17	21.36	3.19
S26C5	E	6.15	393.52	94.54	9.46	9.63	0.16
S27C5	E	5.69	371.12	92.55	12.88	14.49	1.61
S28C5	E	5.65	383.88	88.89	14.30	15.48	1.18
S29C5	E	5.41	393.53	82.96	7.63	8.39	0.76
S30C5	E	6.24	371.51	102.00	20.54	19.68	0.86
S31C5	E	4.58	396.30	84.13	14.75	17.41	2.66
S32C5	E	5.75	350.51	116.65	14.21	17.26	3.05
S33C5	E	6.06	366.29	100.01	6.97	11.20	4.23
S34C5	E	5.03	355.18	95.77	19.14	16.73	2.41
S35C5	E	5.11	374.02	91.60	14.77	15.27	0.50

Sub - Subject, Cond - Condition
Vel - Velocity
Freq - Frequency
T ang GC - Trunk angle at ground contact
T ang TO - Trunk angle at toe-off
Δ T ang - change in trunk angle from ground contact to toe-off

FRequal

Sub/Cond #	Sub group	Hip ROM deg	Knee ROM deg	Ankle ROM deg	H vel TO $deg \cdot s^{-1}$	K vel TO $deg \cdot s^{-1}$	A vel TO $deg \cdot s^{-1}$
S1C5	A	64.23	131.93	54.75	-307.19	465.98	811.99
S2C5	A	53.85	99.19	50.10	-160.66	357.00	779.09
S3C5	A	54.91	115.78	56.49	-256.74	510.37	961.74
S4C5	A	68.24	121.71	50.25	-143.56	350.17	561.13
S5C5	A	61.72	110.49	50.58	-423.45	312.80	668.89
S6C5	A	62.02	117.06	53.05	-240.76	474.35	763.73
S7C5	A	62.57	115.92	52.90	-414.91	378.04	753.74
S8C5	A	57.03	131.02	84.75	-308.15	570.99	704.74
S9C5	A	66.16	109.97	54.12	-278.69	237.37	546.79
S10C5	A	61.71	113.64	55.38	-213.25	350.34	614.54
S11C5	A	53.43	119.91	55.95	-268.47	388.68	865.80
S11C5	A	57.87	96.02	52.16	-270.82	240.30	636.19
S13C5	A	61.58	135.22	58.28	-313.22	260.68	701.27
S14C5	A	63.60	116.34	56.05	-244.05	329.05	703.92
S15C5	A	58.60	125.00	30.95	-105.41	338.88	597.27
S21C5	E	68.86	128.08	86.25	-130.86	385.77	703.83
S22C5	E	73.80	120.31	56.14	-258.22	476.18	905.16
S23C5	E	63.27	119.01	43.50	-247.82	406.01	527.97
S24C5	E	70.43	116.23	78.71	18.89	559.33	738.20
S25C5	E	70.46	130.81	44.73	-95.76	531.27	478.85
S26C5	E	71.94	122.38	49.50	-209.17	344.14	772.31
S27C5	E	59.59	117.12	48.88	-211.45	457.29	763.61
S28C5	E	60.76	124.81	57.56	-257.96	434.42	840.40
S29C5	E	60.98	120.48	55.02	-316.74	461.43	874.83
S30C5	E	65.41	109.45	57.20	-336.72	449.56	811.21
S31C5	E	61.67	124.44	47.78	-198.97	358.95	588.43
S32C5	E	64.73	107.31	37.13	-9.76	636.93	810.26
S33C5	E	54.44	127.16	52.24	-355.10	532.11	412.94
S34C5	E	62.40	113.12	40.38	-218.48	475.60	575.36
S35C5	E	64.91	120.05	53.93	-202.01	464.93	700.24

Sub - Subject
Cond - Condition
Vel - Velocity
ROM - Range of motion
TO - Toe-off
H - Hip, K - Knee, A - Ankle

FRequal

Sub/Cond #	Sub group	Δ height cm	F max V $m*s^{-1}$	H to A (GC) % leg len	H to A (TO) % leg len	ISL % leg len	Stance t ms	I Accel f % BW
S1C5	A	3.81	8.19	38.06	37.92	75.98	188.3	3.69
S2C5	A	3.57	8.87	44.67	52.88	97.56	181.3	1.64
S3C5	A	2.89	9.41	46.28	48.13	94.41	186.0	4.38
S4C5	A	4.93	8.59	47.59	51.92	99.50	205.7	5.27
S5C5	A	5.06	7.25	37.24	39.04	76.28	202.7	0.00
S6C5	A	5.61	8.89	43.24	51.91	95.15	192.5	0.00
S7C5	A	5.84	7.84	52.22	45.36	97.58	191.3	0.00
S8C5	A	2.02	9.96	44.43	39.52	83.95	196.3	8.21
S9C5	A	6.03	7.58	43.68	52.35	96.03	234.7	0.00
S10C5	A	4.17	8.82	34.30	57.23	91.53	180.3	0.00
S11C5	A	5.48	7.71	45.92	41.57	87.49	208.7	0.00
S11C5	A	4.13	7.85	40.40	52.07	92.47	192.3	0.00
S13C5	A	4.29	7.91	40.47	50.14	90.61	181.7	0.00
S14C5	A	6.97	8.31	40.30	55.16	95.45	209.0	0.00
S15C5	A	3.55	8.67	54.70	28.82	83.52	191.0	1.25
S21C5	E	5.51	10.47	41.51	56.04	97.54	173.5	0.00
S22C5	E	2.05	12.58	38.30	59.72	98.02	139.3	11.99
S23C5	E	4.93	10.09	42.74	50.06	92.79	163.3	0.00
S24C5	E	2.63	11.17	46.10	50.23	96.34	176.0	0.00
S25C5	E	2.30	10.65	37.30	22.55	59.85	161.7	0.73
S26C5	E	3.82	10.29	33.66	50.36	84.01	176.0	0.00
S27C5	E	2.00	9.17	45.15	45.93	91.08	169.0	0.00
S28C5	E	5.05	9.42	39.43	48.88	88.31	171.5	0.00
S29C5	E	4.37	9.02	49.00	40.05	89.05	190.0	11.89
S30C5	E	1.84	10.00	43.53	57.98	101.51	171.0	0.00
S31C5	E	6.64	9.63	50.71	48.52	99.24	194.3	0.00
S32C5	E	2.97	11.99	40.34	55.53	95.87	145.0	2.89
S33C5	E	2.60	10.08	45.20	41.66	86.87	134.7	0.00
S34C5	E	3.58	9.05	34.68	52.93	87.61	160.7	0.00
S35C5	E	3.59	10.26	41.65	32.41	74.06	146.7	0.00

Sub - Subject, Cond - Condition, Vel - Velocity
Δ height - change in vertical distance
H to A (GC) - Hip to ankle dist at GC, H to A (TO) - Hip to ankle dist toe-off
ISL - Intrinsic support length
Stance t - Stance time
I accel f - Initial acceleration force

FRequal

Sub/Cond #	Sub group	Imp peak BW	Imp t % stance t	Imp slope BW/s	Resultant active peak BW	Active t % stance t	F brake f % BW
S1C5	A	2.210	15.404	191	3.007	41	0.00
S2C5	A	2.335	14.173	196	2.689	41	0.00
S3C5	A	2.345	14.316	180	3.016	41	0.00
S4C5	A	2.299	12.498	187	2.592	45	0.00
S5C5	A	2.138	15.021	149	2.593	41	0.00
S6C5	A	1.913	8.034	261	2.797	46	0.00
S7C5	A	1.953	16.058	162	2.625	50	0.00
S8C5	A	2.895	18.943	110	2.723	45	0.00
S9C5	A	1.858	15.670	153	2.554	43	0.00
S10C5	A	1.942	11.224	251	3.060	42	0.00
S11C5	A	2.130	12.942	178	2.977	53	0.00
S11C5	A	2.434	14.272	254	2.506	41	0.00
S13C5	A	0.787	4.787	110	2.964	47	0.00
S14C5	A	1.291	7.603	153	2.580	43	0.00
S15C5	A	2.186	16.240	145	2.634	42	0.00
S21C5	E	2.425	14.130	189	2.844	44	0.00
S22C5	E	2.549	12.158	288	3.140	43	-0.17
S23C5	E	2.394	14.361	285	2.844	40	0.00
S24C5	E	1.55	8.32	203	2.64	43	0.00
S25C5	E	1.076	8.134	128	2.941	46	0.00
S26C5	E	0.931	8.818	149	3.469	46	-0.38
S27C5	E	2.176	13.586	227	2.404	48	0.00
S28C5	E	0.679	7.580	103	3.255	47	0.00
S29C5	E	2.239	16.293	171	3.056	43	0.00
S30C5	E	1.300	8.333	137	2.885	45	0.00
S31C5	E	2.197	11.987	206	2.913	42	0.00
S32C5	E	2.626	13.840	269	2.767	42	0.00
S33C5	E	2.46	14.28	264	2.33	43	-0.02
S34C5	E	2.860	22.202	133	3.079	40.63	0.00
S35C5	E	1.085	3.83	194	3.568	29.54	0.00

Sub - Subject, Cond - Condition, Vel - Velocity
Imp peak - Impact peak, BW - Body weight
Imp t - Impact time, % stance t - Percent stance time
Active t - Time to resultant active peak
F brake f - Final braking force

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