A comparison of ground reaction forces during running and form skipping

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A COMPARISON OF GROUND REACTION FORCES
DURING RUNNING AND FORM SKIPPING

by

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1998

A thesis submitted in partial fulfillment
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ABSTRACT

A Comparison of Ground Reaction Forces During Running and Form Skipping

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Following lower extremity injury an athlete may be able to walk within days, however they may not be capable of running for weeks or even months. During this time, the athletic trainer provides the athlete with progressions to running. One activity that has been used successfully in this progression is the form skip. It remains unknown why the athlete is capable of successfully performing the form skip before they can run.

The purpose of this study was to investigate the ground reaction forces (GRF) during form skipping and running. Healthy subjects (N=9) ran and skipped across the force platform at a speed of 3.83 m·s⁻¹ (±5%) and 1.75 m·s⁻¹ (±5%) respectively. Three GRF variables were analyzed: average vertical GRF, maximum vertical GRF, and braking impulse normalized for time. Dependent t-tests (α=0.05) determined GRF during running were significantly greater than during skipping. In conclusion, running produces greater GRF than form skipping in healthy subjects.
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CHAPTER I

INTRODUCTION

During the rehabilitation of an athlete’s injury, the athletic trainer must prepare the athlete for competition through the exposure to safe, functional activities. These exercises should simulate competition situations. Currently, many functional lower extremity rehabilitation exercises focus heavily on the use of closed kinetic chain (CKC) activities. Clinicians generally accept the difference between open kinetic chain (OKC) and CKC activities as being determined by the movement of the distal segment.\textsuperscript{1,2} Researchers have suggested CKC activities have advantages over OKC activities for rehabilitating certain lower extremity pathologies.\textsuperscript{1,3} CKC activities reportedly pose less risk to patients during knee rehabilitation and are more similar to functional movements when compared with OKC activities.\textsuperscript{1,2}

The distal segment is free to move during OKC activities, such as during knee extension or flexion activities. However during CKC activities, the distal segment is fixed and restricted from movement by a load, such as during a squat exercise. The literature suggests CKC activities produce less shear forces at the knee than OKC exercises.\textsuperscript{2} During CKC exercises hamstring activity helps counteract anterior tibial translation produced by quadriceps contraction.\textsuperscript{2} This co-contraction of the hamstrings and quadriceps helps decrease anterior cruciate ligament (ACL) strain, an essential tenet of rehabilitating an ACL reconstruction.
Not only do CKC exercises decrease shear forces at the knee, they tend to reproduce movements often seen during performance. The lower extremity is typically used in such a manner as to take advantage of the benefits of CKC, such as with walking, running, and jumping.\textsuperscript{2} Optimal function or performance does not result from the isolation of individual muscles but from the integration of all muscles normally involved in a particular action.\textsuperscript{3} Therefore, reconditioning programs should contain joint motion patterns and muscle activation patterns which resemble those that normally occur during the activity.\textsuperscript{3} Clinicians recognize the importance of functional CKC activities and therefore typically include them in their rehabilitation plans. Wilk, Arrigo, Andrews, and Clancy advocate performing CKC activities such as minisquats, weight shifts and balance drills during the first week following ACL reconstruction. During the second and third weeks functional exercises such as lateral lunges, lateral step-ups, front step-ups, and lateral step-overs are introduced.\textsuperscript{4} Despite this early inclusion of functional CKC activities, the athlete may not be capable of running for possibly up to 10 weeks or longer following an ACL reconstruction.\textsuperscript{4}

One of the primary focuses for the athletic trainer during this time is to provide safe activities that aid in the progression to running. One functional CKC activity used in the rehabilitation setting to aid in the progression to running is the form skip.\textsuperscript{5} The form skip, also called form marching or A-drill exercises, is similar to a running drill used in speed development programs. This style of skip emphasizes a high knee march with a skip along with specific upper body mechanics. The form skip typically becomes part of the rehabilitation protocol once the athlete has gained lower extremity strength sufficient to rise on the forefoot of the leg while walking with a high knee march with the other
Clinically and anecdotally, the form skip has been used successfully as a progression in lower extremity injury rehabilitation. However, it remains unknown why an athlete with a lower extremity injury can often times progress to form skipping before they are capable of running.

Not only does a lack of information regarding the form skip to run progression exist, but there is also a shortage of research pertaining to the mechanics of form skipping. The majority of the information related to skipping has been obtained through observation. In fact, a comprehensive search of the literature resulted in only one study regarding the mechanics of the skip.

A common way to examine the mechanics of a gait pattern is to analyze the ground reaction forces (GRF). GRF result from an object exerting a force on the ground and can be measured using a force platform. GRF reflect acceleration of the body’s center of gravity, forming part of the descriptive data that characterize the mechanics of gait. GRF have been used as the primary descriptive component in the analysis of the support phase of locomotion. This descriptive data provides insight into the timing of specific events and forces produced during locomotion. Munro, Miller and Fuglevand point out that during rehabilitation of lower extremity injuries, GRF data can factor into the assessment of the progression of the athlete. Typically, as healing progresses the individual’s running speed increases. Furthermore, since almost all GRF variables are running speed dependent, the authors maintain the importance of considering this factor.
Statement of Problem

Typically during knee rehabilitation, patients walk unassisted after quadriceps strength and control reach a level sufficient to maintain proper gait. However, the progression to running may take weeks. A challenge for the athletic trainer during the period between walking and running is to expose the patient to safe progression activities that will assist in this transition. Clinically, form skipping has been successfully used to progress from walking to running. Clearly, this indicates that skipping to running can be a functional progression. However, the relationship of GRF of running and form skipping remains unknown.

Statement of Purpose

The purpose of this study was to investigate selected temporal and kinetic parameters describing the support phase during form skipping and running in healthy subjects.

Significance of Study

Safely returning an athlete to full activity after injury is the primary focus of the athletic trainer. Currently functional CKC rehabilitation is the center of much of that attention. Although many of these activities employed by the athletic trainer produce the desired effect, the underlying mechanisms remain unidentified. If knowledge of the rehabilitation of the injured athlete is to continue to grow, then many of the commonly used practices need systematic examination.
Null Hypothesis

No significant differences between the selected temporal or kinetic variables will exist between running and form skipping.

Limitations

The following were limitations to the current study:

1. GRF reflect the total body's center of gravity acceleration which is not a particularly sensitive measure.\(^9\)

2. No information concerning the joint reaction forces can be extrapolated using GRF. Therefore, no information concerning the forces acting on the joints can be attained.

3. Although GRF may provide evidence for asymmetries or differences between experimental conditions they are incapable of identifying the specific mechanisms causing the asymmetries.\(^9\)

4. The use of healthy subjects limits the extrapolation of the findings to the injured population.

5. During rehabilitation protocols, speeds of skipping and running are typically self-regulated by the patient. However, in this study, the speed of activity was experimentally controlled.

6. The size and use of only one force platform did not allow collection of both phases of the form skip. Thus only one phase of the skip could be examined in this study.
Definition of Terms

The following definitions were used in this study and are presented for clarification.

**Childhood Skip**- A common gait pattern seen in children after galloping and hopping. A skip is a combination of a step and a hop on one leg, followed by a step and a hop on the other leg.\(^\text{10}\)

**Form Skip**- A form running drill which emphasizes a specific running form. A high knee march with a skip along with proper upper body running mechanics is stressed. Also called form marching and A-drill exercises. (Appendix A)

**Force Platform**- A device that is used to record the GRF acting on the person.

**Ground Reaction Force (GRF)**- The force exerted by the force platform on a person in response to the force exerted by the subject on the force platform.

**Anteroposterior Force (Fy)**- Force exerted parallel or horizontal to the direction of travel of the subject. Also termed braking-propulsion force.

**Vertical Force (Fz)**- Forces that act perpendicular to the running surface.

**Impulse**- The area under the force-time curve.

**Healthy Subject**- Subject experiencing no history of lower extremity injury in which treatment was received for longer than seven days, no history of lower extremity ligament surgery, and no current musculoskeletal injury at time of data collection.

Summary

The scientific knowledge base related to rehabilitation of athletic injury continues to grow. Currently, much of the focus is on incorporation of CKC activities throughout
the rehabilitation of the athletic injury. CKC activities are emphasized because they pose less risk to the patient and tend to be more functional. Since movements are completed by integrating several joints and muscles concurrently, it seems reasonable to include CKC in rehabilitation. Although functional CKC activities are stressed in rehabilitation protocols, much about their underlying mechanisms remains unidentified.

The form skip is a functional activity used in rehabilitation that is not well understood. Form skipping has been used successfully as a progression to running after the athlete demonstrates the ability to walk. This period from walking to running often presents difficulties to the clinician simply because of the length of time. Therefore, the aim of the athletic trainer during this time is to present the athlete with safe progression activities.

Why athletes recovering from injury are capable of performing the form skip before they can run remains unknown. Through the examination of the mechanics of both skills some insight might be gained as to why this occurs. GRF have been used extensively in the research to describe the body's center of gravity movement during the support phase of gait. However, the kinetics of form skipping has not been reported in the literature.

The purpose of this study was to investigate selected temporal and kinetic parameters during the support phase of form skipping and running in healthy subjects.

There is a lack of information in the recent literature concerning the forces produced by skipping. By investigating the mechanics of the skip, particularly the form skip, knowledge may be gained concerning this gait pattern. With this knowledge the clinician may be able to understand why the athlete recovering from lower extremity
injury is capable of skipping before they can run. This information may then aid in the development of other functional rehabilitation activities perhaps speeding up the return to full activity.
CHAPTER II

REVIEW OF RELATED LITERATURE

Introduction

The purpose of this study was to investigate selected temporal and kinetic parameters describing the support phase during form skipping and running in healthy subjects. This chapter presents related literature. Initially, literature related to skipping will be discussed. Secondly, studies and literature related to ground reaction forces will be reviewed, including commonly analyzed variables. Next, information related to CKC activities will be discussed. A summary concludes the chapter.

Skipping

A well-known gait children adopt after they learn to run is skipping. The skip, a familiar developmental skill, has been described primarily based on observational data.\(^\text{11,12}\) In children, skipping typically emerges after galloping and hopping, both of which follow running.\(^\text{10}\) Skipping usually first appears around age four and most children become proficient skippers by age seven.

A skip is a combination of a step and a hop on one leg, followed by a step and a hop on the other leg.\(^\text{10}\) Skipping differs from pure walking because it has a significant flight phase, and from pure running because a double support phase often occurs.\(^\text{12}\)
The basic skipping pattern has several components. The skip is initiated by a step. The step of the leading leg is followed by a small hop on the leading leg, which has little horizontal displacement. At the beginning of the hop of the initial leg the trailing leg begins a step. At this point the person is airborne. While in flight the trailing leg moves ahead of the initializing leg and both legs hit the ground in rapid succession where a double support phase occurs. Immediately following the double stance phase the leg in front (formally the trailing leg) takes a small hop completing the cycle.

The only known systematic study on the biomechanics and energetics of skipping appearing in the literature was conducted by Minetti. Minetti was primarily interested in the energetics or the conservation of energy of skipping. He observed that quadrupeds had three primary forms of gait: walking, trotting, and galloping whereas bipeds typically only display two, walking and running. He noticed similarities between bipedal skipping and quadrupedal galloping and questioned whether they were biomechanically and energetically similar. If this were the case then why do children abandon skipping as they mature? The author previously analyzed similar mechanical and metabolic variables on horse locomotion and found that galloping is the fastest gait for quadrupeds and is the best in terms of avoiding injury and minimizing metabolic consumption at fast speeds. Minetti further observed skipping was the favored mode of locomotion on the moon.

To answer those questions Minetti investigated five healthy male subjects during skipping on a treadmill at differing speeds ($1.7 - 3.3 \text{ m}\cdot\text{s}^{-1}$). The motion pattern during skipping was measured by an optoelectronic device consisting of four infrared cameras sampling at 100 Hz. Eighteen reflective markers were positioned on the subject’s joints of interest.
Minetti previously reported quadrupedal galloping as a smooth gait displaying lower forces in muscles, tendons, and bones when compared to trotting at fast speeds. In contrast, Minetti discovered skipping is a jolting gait that produces greater forces than walking or running. The trajectory of the body's center of mass, calculated from the three-dimensional positions of the different segments and reflected by the potential energy range, showed a much higher (about 200%) vertical displacement in skipping than in running at the same speeds. Therefore, Minetti concluded skipping produces higher vertical GRF than running at the same speed because a greater fraction of the stride and the body are off the ground. Minetti also reported that skipping is metabolically more demanding (about 150%) than running at the same speed.

Minetti concluded the reason skipping is the preferred gait on the moon probably relates to the high metabolic cost being overridden by the need for less work against gravity. He further reported that in the case of slippery surfaces, like those found on the moon, skipping can benefit by having the trailing foot (the first to touch the ground after flight) in a more vertical position at landing and immediately be followed in ground contact by the leading foot, therefore increasing the stability of the combined push.

Although Minetti reported skipping produces higher vertical GRF than running at the same speeds, the fact remains skipping has been used successfully in rehabilitation protocols. It should be noted that in the present study, the form skip, a specific type of skipping technique was investigated whereas Minetti investigated a childhood skip. Although childhood and form skipping involve the same basic locomotor patterns, a step and a hop, some differences do exist.
The form skip used in rehabilitation programs has evolved from speed development literature. In the speed development field, form skipping is part of a progression of running drills used to establish efficient, error-free sprinting form.\textsuperscript{14} The drills also help ingrain neuromuscular movement patterns and increase leg turnover and therefore stride frequency.\textsuperscript{14} Allerheiligen defines leg turnover as the period of time from when the foot leaves the ground and touches again. Several varieties of form running or marching exist in the literature. The form skip utilized in this study comes from a group of exercises called "A" drills, which are marching drills that emphasize high knee lift.\textsuperscript{14}

"A" drills are typically taught in a progression of three steps. The progression is as follows: high knee marching drill or A1, high knee marching drill with a skip or A2, and high knee marching drill with a rapid skip or A3.

The athlete typically begins with A1 drills which are high knee lifts with only one leg, often called high knee marches. The knee is flexed with the foot dorsiflexed. The knee is brought up high, with the foot vertically and horizontally level to the opposing knee. Knee flexion allows for a positive shank angle as seen in sprinting and a dorsiflexed foot allows proper footstrike.\textsuperscript{5,15} The footstrike should be a midfoot strike allowing transition to the proper toeing off seen with sprinting.\textsuperscript{5} The opposing leg is fully extended with plantar flexion of the ankle allowing the person to rise on the fore or ball of the foot. Upper body mechanics contribute significantly to the mastery of the skill since a great deal of force production comes from the upper body. The torso should be angled slightly forward to mimic a form seen with sprinting. Elbows are flexed at about 90° with the arms thought of as pendulums with the shoulder as the pivot point.\textsuperscript{14} The hands move from shoulder to hip level through the entire range of motion in a snapping
or punching action and in opposition to the ipsilateral leg.\textsuperscript{14,15} Once mastered on one leg, the process is repeated with the contralateral leg. Once mastered on both legs the progression is to continuous, alternating legs.

After mastery of continuous A1 drills, the athlete is progressed to A2 drills, which mimic A1's, but with a moderate paced skipping action.\textsuperscript{14} The mechanics of this drill are the same as the previous except as the athlete rises on the forefoot a small hop is introduced. The introduction of the hop thus produces a skipping pattern similar to that of the childhood skip. The major difference between form and childhood skipping is the position of the knee and of the arms. In a childhood skip, the swing leg or trailing leg is not flexed like in the form skip. Furthermore, the arm action is different. In both forms of skipping, the arms move in opposition to the ipsilateral leg, however in the form skip the elbows are flexed and perform a snapping action not seen in the childhood skip.

After mastery of A2 drills on alternating legs, progression is to A3 drills. This level utilizes very rapid leg and arm movements with a rapid skipping action.\textsuperscript{14} Allerheiligen suggests the rate of this skip should be similar to the rate of sprinting. However, he points out the emphasis is not on horizontal speed. Nowhere in the literature is there reference as to the optimal skip speed.

A similar progression is used in the rehabilitation setting where the emphasis is not on high speed skipping, but rather on proper form.\textsuperscript{5} The athlete most likely will not be able to perform at a sprint speed typically observed in A3 drills, however they perform faster than the speeds seen with A2 drills. The clinician simply allows the patient to skip at a pace comfortable to them.\textsuperscript{5}
Ground Reaction Forces

Ground reaction forces are forces exerted by the ground on the body. According to Newton’s third law, GRF are equal in magnitude but opposite in direction to the forces exerted by the person on the surface. During locomotion, GRF data reflect the acceleration patterns of the total body’s center of gravity, forming a part of the descriptive data characterizing the mechanics of gait. Ground reaction force-time histories have been used as the primary descriptive component in the analysis of the support phase of locomotion. The analysis of GRF during locomotion can provide valuable information about basic locomotor mechanisms. In turn, the data can be used to evaluate normal as well as pathological gait.

GRF are broken down into three orthogonal components: vertical, anteroposterior, and medial-lateral. The vertical components act in a plane perpendicular to the running surface. The anteroposterior, also termed braking-propulsion, reflect the forces exerted parallel or horizontal to the direction of travel. Medial-lateral forces also act on the body horizontally, however not in the direction of travel but perpendicular to it.

GRF during walking and running have been examined extensively in the literature. A wealth of research exists investigating GRF during walking and running, but a lack of information exists on GRF during skipping.

Walking and running exhibit somewhat different GRF patterns. Nilsson and Thorstensson studied the differences in GRF patterns during walking and running at the same speed. In their study, 12 healthy active males walked and ran across a force platform at varying speeds (1.0 – 3.0 m·s⁻¹ during walking and 1.5 - 6.0 m·s⁻¹ during
Many of their results correlated with previous data but provided one of the first attempts to measure GRF during walking and running at the same speed.

They reported the typical vertical GRF curve for walking consists of two peaks with an interadjacent trough. Furthermore, across the walking speeds tested, the mean vertical amplitude of the first peak of the stance phase increased from 1.0 bodyweight (BW) to 1.5 BW from the lowest to highest speed. The second peak was approximately equal to the first peak at the lowest speeds but plateaued at 1.2 BW at the highest speeds. The trough decreased progressively with speed from 0.9 BW to 0.4 BW at 2.5 m·s⁻¹. The trough would coincide with the highest location of the center of gravity. The authors point out the center of gravity is elevated during single support and reaches its peak height approximately at mid-support. The trough should then coincide with this position, since deceleration upwards followed by acceleration downwards causes an unloading on the ground. However, during running the situation is reversed and the center of gravity’s lowest vertical position occurs during midstance.

Different foot-strike patterns influence the appearance of the force curve during running. Runners who strike the ground with the rearfoot consistently exhibit an impact peak. This initial peak of high force and short duration does not appear in mid and forefoot strikers. Evidence exists to suggest a positive relationship between the magnitude of the impact force and overuse injuries in running, degenerative changes in joints and low back pain due to the transmission of shock waves through the musculoskeletal system.

Nilsson and Thorstensson also reported that during walking the anteroposterior force curve usually has a small initial propulsive force peak followed by a posterior-
directed braking force which changes into a propulsive force near mid-support. The initial propulsive force is attributed to the push off of the contralateral leg.

During running the anteroposterior GRF has typically been characterized as predominately biphasic. The initial phase is considered a braking force while the latter a propulsion force. Munro et al. reported the pattern of braking force is variable across subjects. In their study 20 male, predominately rear-foot strikers, ran across a force platform at speeds of 2.5 to 5.5 m·s⁻¹. They reported that five subjects had Fy patterns which demonstrated peak breaking occurring at approximately 25 percent of the total stance time. A second group of 10 subjects had bimodal braking peaks generally occurring at seven and 24 percent of the stance period. The five remaining subjects displayed multiple braking peaks. This finding is contrary to reports in previous studies. Hamill, Bates, Knutzen, and Sawhill reported the braking force of rear-foot strikers was characterized by two peaks whereas midfoot strikers displayed a single peak. In contrast, Cavanagh and Lafortune reported a single peaked curve for rearfoot strikers and a double peaked pattern for the midfoot strikers. Nilsson and Thorstensson reported that both fore and rearfoot strikers displayed double peaks, however the double peaks were less predominant in the rearfoot group. Munro et al. point out the association of foot-strike patterns with specific braking patterns is not as straightforward as previously believed.

The shape or pattern of GRF curves also change with speed. As an individual increases speed, both stride length and stride frequency increase. The increase in stride length places the center of gravity farther behind the point of ground contact resulting in a larger braking force. At faster running speeds, the greater braking force imparted to the ground by the runner causes a greater change in momentum at ground
contact than at slower running speeds. Since the leg is not oriented in any of the orthogonal planes, the differences in the magnitude of contact force should be evident in each force component.

Examining the GRF curves not only involves examining the shape of the entire pattern but also reducing the curve into its components or variables. Certain variables more than others have been examined in the literature. Variables pertaining to this study are subsequently discussed.

The vertical GRF component has received the most attention in the literature. According to Miller, this can be explained by the fact that force-time history is the most straightforward and hence easiest to quantify for comparative purposes. This component is also popular because the magnitude of $F_z$ is greater than $F_y$ or $F_x$.

Stance time or contact time begins when the GRF curve deviates from the zero line and terminates when the GRF curve returns to and remains at zero. Typically the vertical component of the curve is selected as the basis for stance time. However, Miller points out there is a certain amount of drift or fluctuation above and below the baseline voltage emitted by the force platform amplifiers. Therefore researchers typically designate some arbitrary value slightly above zero volts to designate when footstrike and toe-off events occur. The GRF threshold value has varied between authors. For example, Munro et al. in their study used a threshold value of 16 N and found the stance time decreased from 270 to 198 ms as the speed increased. Those values differ somewhat from those reported by Cavanagh and Lafortune. In their study of seventeen runners (10 male and 7 female) running at a pace of 4.5 m·s$^{-1}$ they reported that stance time was an average of 188 ms, roughly 25 ms shorter than what Munro et al. reported. Munro et al.
discovered that if they had set the threshold value at 50 N, like Cavanagh and Lafortune had, then their stance times would have decreased by 2-4 ms at the onset and 10-15 ms at the end of the stance period. This observation underlies the importance of reporting the minimum vertical force accepted as 'signal' if ground contact times are to be compared across studies. Miller concluded that 50 N be used since the foot may still be undergoing some positioning at the very beginning of the stance.

According to Miller, if the vertical GRF for running had to be described by a single variable, the most meaningful variable would be the average vertical GRF. The average vertical GRF reflects the vertical GRF throughout the entire stance phase. The average vertical GRF is quite stable when compared with other variables that can be examined. This is due to the fact that intra-individual variance has less of an effect on the outcome. Munro et al. point out that because of the small intra-subject variability only small differences would be detected with trials of running at similar speeds. They continue by saying that if differences are of sufficient magnitude to be reflected in the average vertical GRF, the investigator or clinician could be reasonably confident that there were functionally significant differences in the running pattern. Therefore, the average vertical GRF can be used to monitor treatment programs which result in changes in the vertical acceleration of the total body center of gravity. For example, a positive relationship between average vertical GRF and running speed can be observed. Munro et al. reported that average vertical GRF increased significantly from 1.40 BW at 3.0 m·s⁻¹ to 1.70 BW at 5.0 m·s⁻¹. Hamill et al. reported similar findings.

Although average vertical GRF may be the single most meaningful variable, other variables possess merit. During running, the first peak seen on the vertical curve is the
impact peak. As previously discussed, the impact peak is typically only seen with rearfoot strikers. In mid-foot strikers, only a vestige if anything remains of the impact peak. Munro et al. reported in their investigation that the impact peak occurred between six and 17 percent of the total stance time and its magnitude increased from 1.6 BW at 3.0 m·s⁻¹ to 2.3 BW at 5.0 m·s⁻¹, similar to what Hamill et al. found. The impact peak is produced due to contact with the ground. Prior to ground contact the foot travels downward yet once the foot contacts the ground there can be no vertical velocity. However the velocity of the lower extremity still must decrease to zero, this results in a production of a shock wave. The shock wave travels through the body and the energy must be dissipated. The body accomplishes this energy dissipation through the use of certain structures, including muscles, bones, and viscoelastic components of joints, such as meniscus, articular cartilage, and intervertebral discs. This repetitive dissipation of the shock wave by these structures has been implicated as the etiology of certain pathological conditions, in particularly joint degeneration. Considerable evidence exists that correlates the magnitude of the impact force and microtrauma to soft tissue and bone. Such conditions as osteoarthritis and low back pain seem to be progressed do to repetitive impact forces.

Another variable of interest is the vertical maximum peak. Midfoot and forefoot strikers only display a single vertical peak. However, as discussed, rearfoot strikers display bimodal peaks. Following the impact peak (F₁) there is another peak, F₂. Typically F₂ is greater in magnitude then F₁, however in some cases F₁ exceeds F₂. The F₂ peak typically occurs between 35 and 50 percent of total stance time during running. As previously discussed maximum peaks increase with speed. During
walking, Nilsson and Thorstensson reported F1 increased from 1.0 to 1.5 BW and F2 leveled off at 1.2 BW across the speeds they tested. During running, they reported the F2 increased with speed from approximately 2.0 BW to about 2.9 BW. This is similar to findings of Munro et al. and Hamill et al.

In midfoot and forefoot strikers, where the impact peak is absent, the quantification of the initial part of the vertical GRF curve may be effectively characterized by the loading rate. Munro et al. calculated loading rate by determining the time required for the vertical force to rise from 50 N to body weight plus 50 N. The selection of one BW change is arbitrary, simply made to facilitate comparison across runners. According to Miller, at running speeds between 4.0 and 4.5 m·s⁻¹, the relative degree of shoe hardness is negatively related to the rise in the initial portion of the vertical GRF curve and thus positively to the loading rate. Munro et al. also report that loading rate is positively related to running speed, increasing from 77 BW·s⁻¹ at 3.0 m·s⁻¹ to 113 BW·s⁻¹ at 5.0 m·s⁻¹, however no attempt was made to control for shoe type in the study. Miller points out that loading rate would be important to monitor in cases where the runner is recovering from lower extremity injury. It would seem logical that as healing progressed loading rate would increase as well.

Similar to loading rate but opposite in direction is decay rate. Following the peak vertical GRF, the curve drops back to zero as the runner enters the flight phase. The rate at which this occurs is called the decay rate. Like loading rate, decay rate is calculated by measuring the rate at which the force dropped from BW plus 50 N down to 50 N. The decay rate is smaller than the loading rate by a factor of five and is higher for faster speeds. Munro et al. reported that the decay rate increased from 14.6 BW·s⁻¹ at 3.0 m·s⁻¹
to 23.9 BW·s⁻¹ at 5.0 m·s⁻¹. Determination of the decay rate can provide insight regarding
toeing-off behaviors of the runner. Miller points out in cases where the decay rate is
prolonged there may be a problem with slipping. This is the case with below-knee
amputees, therefore the individual is advised to avoid running on smooth surfaces such as
gymnasium floors.⁹

A change in vertical velocity gives information regarding the runner’s ability to reverse the downward velocity of the center of gravity at touch-down to an upward velocity at take-off.⁶ This variable is calculated by subtracting the body weight impulse from the vertical GRF impulse and dividing the mass of the subject.⁶ Munro et al. reported this variable significantly increased from 1.0 to 1.5 m·s⁻¹ as the running speed increased. It should be noted however from GRF records alone it is not possible to determine the person’s velocity at initial or final contact but only the change in velocity that occurs during the stance period.⁹

As discussed previously, the anteroposterior GRF observed varies during walking and running. During walking the force curve usually has a small initial propulsive force peak followed by a braking force followed by a propulsive force at about mid-support.¹⁶ During running, the anteroposterior GRF has been typically characterized as predominately biphasic.⁶ Although reasonably constant within subjects, the pattern of braking force may be variable between subjects.⁵⁹ In their study, Munro et al. reported that a quarter of the subjects displayed a single braking peak, while a half exhibited double braking peaks, while the other quarter of the runners demonstrated multiple braking peaks. As discussed these findings are contrary to what has been found in previous studies that have associated braking peaks with footstrike patterns.⁷,⁸,¹⁶
Maximum braking and propulsion forces are simply as the name describes, peaks in each direction. Like most other GRF components, Fy is sensitive to changes in running speed. As reported previously, a small initial propulsive force is seen with walking, however this does not change with speed. Yet the braking and propulsive forces in the same study increased linearly from about 0.15 BW at 1.0 m·s⁻¹ to 0.3 BW at 2.5 – 3.0 m·s⁻¹. The authors also reported that the peaks increased linearly for running as well, from 0.13 BW to 0.5 BW as speeds increased. No systematic differences in peak forces were reported between rearfoot and forefoot strikers.

A transition time is present from the end of braking to the beginning of propulsion. This is simply called transition time or zero fore-aft shear. This variable measures the relative time required for the center of gravity to pass over the base of support. As Miller explains, during running there technically is zero fore-aft shear at least three points along the GRF history, one before initial braking, one after braking and before propulsion, and one after the propulsion, however the term is typically reserved for the time between braking and propulsion. Both Cavanagh and Lafortune and Munro et al. have reported a value of 48 percent across a range of roughly 3.5 to 5.0 m·s⁻¹. Hamill et al. reported values from 50 to 43 percent over a range of 4.0 to 7.0 m·s⁻¹. Although it appears there is a negative relationship between running speed and the time of transition, the trend may be somewhat accentuated by the possibility that subjects running in excess of 6.0 m·s⁻¹ may not have attained their maximum speed by the time they reached the force platform and therefore would be spending a greater proportion of their time in propulsion than would be the case if they were running at a constant speed.
Another variable that can be determined by examining the zero fore-aft shear is the time to transition. Hamill et al. found relative time from initial contact to transition was the only relative timing of key events variable that was significantly different across running speeds. They found that as running speed increases the time to transition occurs sooner relative to the total support time. The authors hypothesized that this was due to the rearward motion of the foot and leg relative to the center of gravity bringing the limb slightly more under the body at ground contact.

Impulses are the area under the force-time curve. Braking and propulsive impulses should be equal in magnitude but opposite in direction if the person maintains a constant horizontal velocity as they cross the force platform. Because of this relationship, braking and propulsive impulses are often used as an objective criterion as to whether the individual has maintained a constant velocity.

In walking, the braking and propulsive impulses display an inverted U shape in relation to velocity. At higher speeds of walking, the braking impulse was somewhat lower than that of braking and reached its maximal value of 27 Ns at 2.0 m·s⁻¹. Nilsson and Thorstensson reported that with running the braking and propulsive impulses were approximately equal at all speeds, with no difference observed between foot strike patterns. At 1.5 m·s⁻¹ the impulse was 12 Ns and increased to about 18 Ns at 6.0 m·s⁻¹.

Impulses are typically reported in Ns, however, they can be normalized by dividing each by the impulse of the individual's body weight over the entire stance time, yielding units of body weight impulse (BWI). This conversion simply allows comparison across subjects.
Closed Kinetic Chain

Steindler derived the term kinetic chain from the closed kinematic and link concept in mechanical engineering. In the link concept, rigid overlapping segments are connected in series by pin joints. The system is considered closed if both ends are connected to an immovable framework, thus preventing translation of either the proximal or distal joint center. This linkage creates a system where movement at one joint produces movements at all other joints in a predictable manner, and is called a closed kinematic chain. Steindler noticed that the extremities could be thought of as rigid, overlapping segments in series. He noted two types of kinetic chain exist in the extremities under different limb loading conditions. He observed that when the foot or hand meets considerable resistance, muscle recruitment and joint motion differ from that seen when the foot or hand is completely free to move. The difference was significant enough to warrant distinguishing the two conditions with separate terms. An open kinetic chain is when the peripheral joint of the extremity can move freely, such as in the swing phase of gait. Conversely a closed kinetic chain exists whenever the foot or hand meet considerable resistance, such as with a squat. He hastened to point out that a true closed kinetic chain only exists during isometric exercise, since by definition neither the proximal nor distal segment can move in a closed system.

Reports in the literature allude to the idea that CKC exercises pose less risk to the patient recovering from knee injuries, in particular a decrease in ACL strain. According to Palmitier et al. from a theoretical standpoint, a decrease in ACL strain during a weightbearing exercise has been explained by hamstring activity. Co-contraction of this muscle group helps neutralize the tendency of the quadriceps to cause
anterior tibial translation. This may seem paradoxical at first since the hamstrings are classified as a primary knee flexor, but they also function as a strong hip extensor. Therefore, according to the authors, during weightbearing exercises, such as the squat, a forceful hamstring contraction is induced to stabilize the hip flexor moment, which then has the secondary effect on the knee.

Decreased knee shear is not the only advantage for the use of CKC activities in rehabilitation. When the human body functions, different muscle groups work simultaneously. For example, walking, running, and jumping are all activities which exploit the kinetic chain. Since optimal performance is the result of the integration of all joints and muscles involved in the particular action it would only seem natural that the body be rehabilitated or trained in this manner. This idea of functional or sport-specific rehabilitation theoretically allows the central nervous system to ingrain the correct movement pattern. Palmitier et al. point out that repetitive deviation from this pattern can result in incorrect and inefficient muscular recruitment patterns that can hinder performance.

Furthermore, Palmitier et al. continue to highlight the need for CKC activity by examining the simultaneous hip and knee extension seen when rising from a squat. They point out both the rectus femoris and the hamstrings are active. As the hip extends, the rectus femoris lengthens while the hamstrings shorten, but as the knee extends the rectus femoris shortens and the hamstring lengthens. Steindler called this a concurrent shift, something unable to be reproduced in isolation or OKC exercises.

Traditionally, following lower extremity injury OKC activities have been used early on during rehabilitation, while CKC exercises being implemented once the patient
is able to bear weight on the injured extremity. For example, Wilk et al. suggest in their accelerated rehabilitation protocol for ACL reconstruction that the first several days following surgery that the athlete perform no CKC exercises until the athlete is able to tolerate weightbearing. Instead, the athletic trainer and the athlete should focus on OKC range of motion exercises such as straight-leg raises, ankle pumps, and active and passive knee flexion and extension. The authors suggest that by days four through six post-surgery, the athlete should begin CKC activities. These drills include minisquats (0 - 45°), weight shifts, balance drills, and proprioceptive training activities. Although the patient may be able to perform these weightbearing activities they still may require crutches to ambulate. Once the patient attains enough quadriceps strength and control to walk unassisted they typically can begin to perform more functional CKC activities, such as step-ups and step-overs, stair stepper machine, and walking programs. However, despite this accelerated program the athlete still may not be able to jog or run for at least ten weeks, perhaps longer. During this time the athletic trainer must prepare the athlete for the progression from walking to jogging. Once such progression that has been used successfully is the use of the form skip. This skill not only is a functional CKC exercise allowing for the aforementioned benefits, but it also helps to teach proper running mechanics. However it is unknown why the athlete may be able to perform this skill before progressing to jogging or running.

Summary

Although skipping is a common gait pattern, very little information on the skill exists in the literature. Much of the information is observational data gained from
observing children perform the gait pattern. Skipping is a combination of a step and a hop on one leg, followed by a step and a hop on the other leg. Interestingly, like walking, skipping has a dual support phase yet has a distinct airborne phase like running. Only one study, Minetti's, exists examining the mechanics of the skill. Minetti was primarily interested in discovering why children abandon skipping as they age. His study suggested that skipping is actually an inefficient gait pattern. Skipping is a jolting gait that produces greater forces than walking or running and is significantly more metabolically demanding than running at the same speed. Despite these findings, a version of skipping, the form skip, has been used successfully in rehabilitation programs. However, the reason form skipping is used successfully is unknown.

Ground reaction forces are the forces exerted by the ground onto the body. Ground reaction force-time histories have been used as the primary component in the analysis of the support phase of locomotion. Examining GRF during locomotion can provide insight concerning basic locomotor mechanisms and give useful data for gait evaluation. Both walking and running have been studied extensively in the literature, however there is a lack of GRF information describing skipping.

Currently, the trend in athletic rehabilitation is to have the athlete perform closed kinetic chain exercises. Closed kinetic exercises seem to pose less risk to the athlete by decreasing shear forces in the lower extremity, particularly at the knee. Furthermore, CKC activities tend to replicate movement patterns that are typically seen in performance. Although CKC exercises are used extensively in rehabilitation many have not been systematically studied.
CHAPTER III

METHODOLOGY

Introduction

The purpose of this study was to investigate changes in selected temporal and kinetic parameters during the support phase of form skipping and running in healthy subjects.

The methodology utilized to fulfill the purpose of the study is presented in this chapter. The material is discussed under the two major headings: collection of data and treatment of the data.

Collection of Data

Thirteen college-aged male varsity athletes were recruited to volunteer as subjects from the University of Nevada, Las Vegas. All subjects signed an informed consent (Appendix B) form approved by the Office of Sponsored Projects (Appendix C). Subjects were screened through the use of a subject questionnaire (Appendix D) prior to participation in the study. Subjects who reported a history of lower extremity injury in which treatment was received for longer than seven days, history of lower extremity ligament surgery, or were currently suffering from a musculoskeletal injury were excluded from the study.
A Kistler Force Platform (Model 9281B) (Kistler Instrument Company, Amherst, NY) connected with a Kistler eight-channel charge amplifier (Model 9856B) interfaced with a CIO-DA516-F analog-digital (A/D) board connected on-line to a Gateway E-3000 personal computer (Gateway Computers, San Diego, CA) was used to collect ground reaction force data. Two channels of ground reaction force data, vertical (Fz) and anteroposterior (Fy), were collected at a sampling rate of 1000 Hz. The force platform was installed in the middle of a 13 m runway in the Sports Injury Research Center at the University of Nevada, Las Vegas. The top surface of the platform was flush with the tile floor, and a tile collar was placed around but not touching the platform to create a complete and safe running surface. Platform mounting consisted of a stainless steel base secured to a concrete block that was an integral part of the building sub-structure. A Brower Timing Light Speedtrap 2 System (Brower Timing Systems, Draper, UT) was placed 2 m apart along the runway to measure horizontal speed. A schematic of the experimental setup is provided in Appendix E. Trials were videotaped using a Panasonic AG-190 VHS movie camera (Matsushita Electric Industrial Company, Osaka, Japan). The videotape was used to insure that the subject made contact with the force platform.

The experimenter initiated data sampling as the subject approached the platform. Sampling continued for 1.5 s after ground contact. Data were stored in Random Access Memory (RAM), graphed, and qualitatively evaluated on a monitor to assure the subject maintained constant velocity during the trial prior to storage on a hard disk for subsequent processing.

All subjects reported to the Sports Injury Research Center and were orientated to the laboratory set-up. Each subject read and signed an informed consent form. Subject
questionnaires were used to determine if the subjects met the criteria as a healthy subject. If the subject did not meet the criteria, they were excused from any further participation in the study. Those who met the criteria were allowed to continue. Subject's height and weight was recorded on the subject questionnaire, height was determined using a wall mounted chart (m) and weight in N by the Kistler Force Platform. Subject information is provided in Table 1.

Subjects completed a five-minute warm-up on a Monark GIH Cycle Ergometer (Monark, Stockholm, Sweeden) set at 1 Kp. While performing the warm-up, the subjects viewed an instructional video describing the components and proper mechanics of the form skip. Following the warm-up and video, each subject completed a training session on the proper mechanics of the form skip. This training consisted of verbal instruction. The instructions followed the training protocol as described previously, beginning with form marching progressing to form skipping. Detailed form skipping instruction is provided in Appendix F. Subjects were allowed to practice form skipping along the runway until they were comfortable performing the drill and proficient at the skill to the experimenter's satisfaction. After mastery of form skipping the data collection session began. Subjects were also allowed to practice running along the runway until they were comfortable running at the predetermined speeds.

Each subject was required to complete 10 successful trials of both form skipping and running at the predetermined speeds. A successful trial was one in which the subject contacted the force platform in a normal stride pattern at the designated pace. Unsuccessful trials were ones in which the subject did not contact the platform, did not contact with the same foot, speed criteria was not met, or subject did not maintain
constant speed across the platform (determined by examining the braking and propulsive impulses of the Fy component on the computer monitor following the trial). If the trial was unsuccessful, the trial data were disregarded and the trial repeated. The subjects were asked to skip across the force platform at a pace of 1.75 m·s⁻¹. This pace was selected based on typical speeds observed clinically. Speed was measured by a photoelectric timing light system. Subjects were asked to run across the platform at a speed of 3.83 m·s⁻¹. Again this selection was based on speeds commonly observed in rehabilitation protocols. Trial order was counterbalanced. The maximum number of attempts the subjects were allowed to complete to obtain 10 successful trials was 30. Speeds were recorded on a data recording sheet for further analysis (Appendix G).

**Treatment of Data**

Three variables were examined in this study, average vertical GRF, maximum vertical GRF (F2), and braking impulse. The average vertical GRF reflects the vertical GRF throughout the entire stance phase.⁶⁹ According to Miller, if the vertical GRF for running had to be described by a single variable, the most meaningful would be average vertical GRF. Maximum vertical GRF is the peak force produced in the vertical direction. As previously discussed, midfoot and forefoot strikers only display a single vertical peak, however rearfoot strikers display an impact peak (F1) followed by a second peak (F2). Typically F2 is greater in magnitude than F1, yet in some cases this impact peak exceeds the second peak. This study only examined the F2 peak. The final variable in this study is the braking impulse. The braking impulse is the area under the curve in
the anteroposterior direction as the limb is slowing down. Braking impulse was then normalized for time.

Identification of ground contact and toe off times were determined to be the point in time when the vertical GRF was greater or less than 50 N, respectively. This value is typically reported in newtons (N). The reason associated with reporting the threshold value in N is because as a person moves across the force platform the deformation of the crystals in the platform produce a voltage. This signal travels to the amplifier, where it is amplified and passed to the analog-digital (A/D) board installed in the computer software. The A/D board converts the amplified volts into N for analysis.

As previously mentioned, due to the size and use of only one force platform both phases of the form skip gait cycle could not be examined. Therefore, during form skipping the first phase of the gait cycle, descent from the trailing leg and propulsion into the hop was evaluated.

The first step in data analysis was to normalize the vertical force-time data by dividing by body mass to allow for between subject comparisons. Three of each subject’s successful trials for each condition were then selected for analysis of each of the three variables. The three trials for running were selected on the basis of the three with the braking and propulsion impulses closest to a ratio of one. For skipping, the three trials closest to the selected speed of 1.75 m·s⁻¹ were chosen for evaluation. After each subject’s trials were selected and averaged a dependent t-test with an alpha level = 0.05 was performed for each of the three variables for form skipping and running.
CHAPTER IV

FINDINGS OF THE STUDY

Introduction

The purpose of this study was to investigate selected temporal and kinetic parameters describing the support phase during form skipping and running in healthy subjects. Subjects were asked to run and skip across the force platform at predetermined speeds. Ground reaction forces were measured in the vertical (Fz) and in the anteroposterior (Fy) directions. Three variables were selected for analysis, average Fz, maximum Fz, and braking impulse of Fy. Separate dependent t-tests were applied to each of the variables at an alpha level of 0.05 to determine if there were significant differences between the conditions. Additional descriptive statistics were calculated.

Analysis of Data

Thirteen male varsity athletes from the University of Nevada, Las Vegas agreed to participate in the study. Four of the subjects were unable to successfully complete the ten trials within the maximum numbers of attempts criteria. Table 1 presents descriptive information of the subjects (N=9). The mean age and standard deviation of subjects was 20 ± 1.3 years. The mean height and weight was 1.80 ± 0.07 m and 848.4 ± 43.24 N respectively.
Table 1
Subject Information

<table>
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<tr>
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<th>Age (yr)</th>
<th>Weight (N)</th>
<th>Height (m)</th>
<th>Sport</th>
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<tbody>
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<td>828.0</td>
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<td>Football</td>
</tr>
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<td>Football</td>
</tr>
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Statistical Analysis of Research Questions

A summary of the means and standard deviations of the variables analyzed during both gait patterns is presented in Table 2. The average Fz GRF was different between running (1.72 ± 0.14 BW) and form skipping (1.31 ± 0.10 BW) (p<0.01, Table 3). The maximum Fz GRF was different between running (2.82 ± 0.32 BW) and form skipping (2.22 ± 0.23 BW) (p<0.01, Table 4). The braking impulse was not significantly different between running (20.16 ± 2.77 Ns) and form skipping (27.36 ± 14.44 Ns) (p=0.16, Table 5). However when braking impulse was normalized for time there was a significant difference between running (191.14 ± 20.92 N) and form skipping (160.02 ± 31.35 N) (p=0.04, Table 6). Finally, Table 7 presents subjects’ average braking time.

Table 2
Summary Table

<table>
<thead>
<tr>
<th>Variable</th>
<th>Running</th>
<th>Skipping</th>
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<tr>
<td>Average Fz (BW)</td>
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<td>1.31 ± 0.10</td>
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<tr>
<td>Max Fz (BW)</td>
<td>2.82 ± 0.32</td>
<td>2.22 ± 0.23</td>
</tr>
<tr>
<td>Braking Impulse (Ns)</td>
<td>20.16 ± 2.77</td>
<td>27.36 ± 14.44</td>
</tr>
<tr>
<td>Braking Impulse Normalized for Time (N)</td>
<td>191.14 ± 20.92</td>
<td>160.02 ± 31.35</td>
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### Table 3
Average Vertical Ground Reaction Force

<table>
<thead>
<tr>
<th>Subject Number</th>
<th>Running (BW)</th>
<th>Form Skipping (BW)</th>
</tr>
</thead>
<tbody>
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</tr>
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<td><strong>Mean</strong></td>
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<td><strong>1.31</strong></td>
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<tr>
<td><strong>Std Dev</strong></td>
<td><strong>0.14</strong></td>
<td><strong>0.10</strong></td>
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</tbody>
</table>

### Figure 1

**Average Vertical GRF**

- **Force (BW)**
  - Running
  - Skipping

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### Table 4

Average Maximum Ground Reaction Force

<table>
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<th>Subject Number</th>
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<tr>
<td>Std Dev</td>
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<td>0.23</td>
</tr>
</tbody>
</table>

### Figure 2

Maximum Vertical GRF

![Graph showing maximum vertical ground reaction force for running and skipping with error bars.](image-url)
Table 5
Braking Impulse

<table>
<thead>
<tr>
<th>Subject Number</th>
<th>Running (NS)</th>
<th>Form Skipping (Ns)</th>
</tr>
</thead>
<tbody>
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Figure 3

![Braking Impulse Graph]

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### Table 6
Braking Impulse Normalized for Time

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<th>Subject Number</th>
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<th>Form Skipping (N)</th>
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### Figure 4

**Braking Impulse Normalized for Time**

![Bar chart showing braking impulse normalized for time](reproduced_with_permission)
<table>
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<th>Subject Number</th>
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SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Introduction

Little information exists in the literature on the skipping gait pattern and much less exists on the role of form skipping in rehabilitation of injury. The purpose of this study was to investigate changes in selected temporal and kinetic parameters during form skipping and running in healthy subjects. The null hypothesis that no significant differences would exist between the selected ground reaction force variables during running and form skipping was not supported for the vertical GRF measured and was supported for the braking impulse. However, when the braking force time was accounted for the null hypothesis is not supported.

Discussion of Results

In summary, 9 healthy male subjects participated in this study. Subjects ran and skipped across a Kistler force platform at speeds of 3.83 m·s⁻¹ (±5%) and 1.75 m·s⁻¹ (±5%) respectively. Ground reaction forces were recorded in the vertical (Fz) and anteroposterior (Fy) directions. Three variables were collected for analysis in this study: average Fz, maximum Fz, and braking impulse. Using a paired t-test, it was concluded that the average vertical GRF was different between running and form skipping. (p<0.01). Additionally, maximum vertical GRF were different between running and form skipping.
skipping (p<0.01). Braking impulse was not different between running and form skipping (p=0.16), however when normalized for time there was a significant difference. Hence, reject the null hypothesis for average and maximum vertical GRF and braking impulse normalized for time and fail to reject the null hypothesis for braking impulse.

The vertical GRF component has received the most attention in the literature because its force-time history is the most straightforward and it is quite stable when compared to other variables. This stability is due to the fact that intra-individual variance is quite low, thus only small differences would be detected with running trials of similar speeds. Munro et al. continue by reporting that if differences are of sufficient magnitude to be reflected in the average vertical GRF, the investigator or clinician could be reasonably confident that functionally significant differences in the running pattern occurred.

Although the results of the average vertical GRF are similar to previous reports in the literature they are greater in magnitude. Munro et al. reported average Fz GRF of 1.53 ± 0.09 BW at 3.75 m·s⁻¹ and 1.57 ± 0.09 BW at 4.0 m·s⁻¹ and Hamill et al. reported similar findings. No previous data exists on GRF during form skipping. Why the average vertical GRF were greater in this study are unknown, possible explanations include type of shoe worn or unfamiliarity with the laboratory set-up. The decision to allow the subjects to wear their own shoes, instead of the same shoes between subjects, was based on the idea that clinically the athletes would not all wear the same shoe. Furthermore, attempts were made to familiarize the subjects with the experimental set-up and protocol thus reducing the effect on the data. Despite the fact all subjects were trained in the proper mechanics of the form skip and allowed sufficient practice time
prior to data collection, the task was a novel skill to several of the subjects. This raises
the issue of unfamiliarity with the form skip; again in the clinical setting some injured
athletes will have previous experience performing the skill while others will not.
Clinically, the novice form skipper will not be taught the skill any different than that of
the experienced form skipper. In all cases the athlete will be progressed through the same
steps, emphasizing the proper mechanics. However, it should be noted that in this study
the average vertical GRF for both running and form skipping are quite constant with a
variance of only 0.02 BW and 0.01 BW, respectively. This means that subjects displayed
similar results within conditions during both gait patterns.

Maximum vertical GRF for running, like average vertical GRF, was significantly
greater in magnitude than form skipping. Like average vertical GRF, the maximum
vertical GRF was also greater in magnitude than previous reports in the literature. The
maximum vertical GRF in this study was 2.82 ± 0.32 BW, while Munro et al. reported
maximums of 2.67 ± 0.16 BW at 3.75 m·s⁻¹ and 2.72 ± 0.17 BW at 4.0 m·s⁻¹. Again like
the average vertical GRF, the maximum vertical GRF displayed a low variance between
subjects for both running (0.10 BW) and form skipping (0.05 BW). Subject four did
display a maximum force during skipping (2.29 BW) greater than that during running
(2.23 BW). The difference was quite small and no explanation exists as to why.

Braking impulse between running and form skipping was not significantly
different. The braking impulse observed during running is nearly identical to those
observed by Munro et al. However there was a great deal of variability observed between
subjects during braking, especially during form skipping. Inspection of the data reveals
that one subject, number five, displayed a large braking force compared to other subjects. This explains why the variance was so large during form skipping.

As previously stated, the braking impulse is the sum of the area under the curve. If the stance phase of the gait is longer then subsequently this area would be greater. This was the case with running and form skipping. Form skipping was measured at a pace of 1.75 m\(\text{s}^{-1}\), whereas running was measured at 3.83 m\(\text{s}^{-1}\), therefore the braking phase of form skip was longer than that of running. Because of this, the braking impulse data is skewed because it does not take into account the time of the braking force. When the braking impulse is normalized to time, the braking force during running is significantly greater than that of form skipping (p=0.04). This supports the hypothesis that form skipping is a mechanical progression to running.

It appears based on the GRF data that form skipping is a mechanical progression to running. This may explain why the athlete recovering from lower extremity injury may be capable of form skipping before running.

Form skipping, like walking has a dual support phase, and like running has a flight phase or period of nonsupport. Although the flight phase during form skipping is much shorter than that of running. This observation could help explain why form skipping is a progression to running. The dual support phase may allow the subject to decrease the need to exert force on the leading leg, the leg on the force platform. Furthermore Nilsson and Thortensson reported that the double support phase duration decreases with speed, which reduces the need to counteract the braking impulse of the contralateral leg. This may especially be true with the injured athlete who unknowingly utilizes protective mechanisms to protect the injured area. For example, the athlete who
form skips for the first time following injury may not exert as much force on the healing leg as they might several weeks after form skipping. He or she knowingly or unknowingly recognizes that the healing leg is unable to withstand the forces so they might compensate by exerting more force on the uninjured leg. Yet as time progresses and the leg is stronger and able to withstand more force, the body recognizes this and reacts accordingly by exerting more force with the healing leg. This could not be examined in this study because only one force plate could be used and the study only examined healthy subjects. Whatever the reason, it appears that the short flight phase of form skipping is just enough to provide a progression to running in the injured athlete.

Kinetic analysis, like those performed in this study, only provides information about the GRF produced during the movement. In order to examine the joint reaction forces, a kinematic analysis must be performed. One limitation of this study is that it remains unknown what joint forces are produced during form skipping. This area of study is of interest in order to determine the shear forces at the joints, especially the knee. Following a knee injury or surgery, particularly an anterior cruciate ligament reconstruction, the athletic trainer must limit the amount of shear forces the athlete experiences at the knee in order to protect the new graft. Although the data provides no information regarding the shear forces, some conjectures can be made based on the forces observed. Upon observation, it appears during form skipping there is less knee flexion occurring than during running. Because of the smaller degree of flexion it can be hypothesized that less shear forces are occurring at the joint. In theory, the greater forces observed during running in this study support this. This also may true at other joints.
along the kinetic chain. However, without the kinematic data this cannot be substantiated.

Additionally, it has been hypothesized that athletes are able to tolerate vertical movements over horizontal movements when recovering from injury. This idea can be observed clinically but evidence supporting this in the literature is nonexistent. The reasons for this are not totally understood but possible explanations include reduced eccentric action and decreased shear forces. Theoretically, during gait patterns, if the movement exhibits more horizontal than vertical displacement of the center of gravity, there is a greater need for an increased eccentric muscle action to slow the limb down. The same is typically true for shear forces. For example, skipping seems to have more vertical than horizontal displacement of the center of gravity, unlike running which maximizes both vertical and horizontal displacement of the center of gravity. This would theoretically reduce both shear forces and eccentric muscle action during form skipping. Thus allowing the athlete to complete the movement without as much muscular and joint force.

Finally, not only does the form skip help progress the injured athlete from walking to running, it helps the athlete develop better running mechanics. The "A" drill exercises were originally developed as running drills to enhance speed development through proper mechanics. Therefore, as the athlete is performing the drills in rehabilitation they are improving their running mechanics, such as leg and arm drive, triple extension, and positive shin and torso angle. In conclusion not only is the athlete recovering from injury but he or she is also becoming a more mechanically "sound" athlete, hopefully decreasing the chance of injury in the future.
Conclusions and Recommendations for Further Study

In conclusion, vertical ground reaction forces and braking forces over time during running were significantly greater than during form skipping. No differences were observed between the braking impulses. These findings suggest that form skipping is a mechanical progression to running. This may explain why when recovering from lower extremity injury the athlete is capable of form skipping before they can run. However, several unanswered questions still exist concerning form skipping.

One of the greatest limitations of this study was only one phase of the form skip could be measured in this study due to the use of only one force platform. The experimenter decided to examine the first phase of the skip, the braking phase. This phase was chosen due to the eccentric component observed during deceleration. Due to the difficulty of performing the eccentric component, the experimenter felt this phase of the skip was of the most value in addressing the purpose of the study. The choice of the eccentric or braking phase therefore did not allow for the examination of the propulsion phase. This phase is an important component of form skipping and needs to be examined in future studies in order to obtain a better understanding of the complete gait cycle of the form skip. Therefore, in future studies the use of two force platforms would be useful in order to examine both phases of the skip concurrently.

This study only examined healthy subjects, as previously discussed it would be of value to examine the ground reaction forces during form skipping and running of athletes who are recovering from injury. This analysis would not only provide information of forces produced by injured subjects but could also perhaps be used as a determination of progression following injury. For example, if kinetic and kinematic data were collected
on a large number of healthy and injured subjects a progression standard could be developed. Munro, Miller and Fuglevand point out that during rehabilitation of lower extremity injuries, GRF data can factor into the assessment of the progression of the athlete. Typically, as healing progresses, the individual’s running speed increases. Furthermore, since almost all GRF variables are running speed dependent, GRF data could be used as a factor to be considered when progressing the athlete.

Only two speeds were examined in this study, 1.75 m·s⁻¹ for form skipping and 3.83 m·s⁻¹ for running. These speeds were chosen because they are speeds typically observed clinically, however it should be noted that in rehabilitation the speed is patient dependent. In other words, the clinician instructs the patient to skip and run at speeds they are comfortable performing at. Therefore the experimenters selected speeds most closely related to speeds observed clinically.

Another limitation of this study is that it remains unknown what joint forces are produced during form skipping. A kinematic analysis, combined with kinetic information could determine if less shear forces are produced during form skipping compared to running as well as the location of the force application. Information could also be obtained about forces at the hip and ankle joints as well, perhaps leading to other factors that allow the athlete to progress to running.
APPENDIX A

PICTURE OF FORM SKIP
Information
Welcome to the Sports Injury Research Center Lab. You are invited to participate in a study of skipping and running. There are minimal risks and the testing should be completed in approximately 30 minutes.

Procedures
If you decide to participate, you will be asked to run and skip across a force platform which measures forces that you produce. You will be trained in the proper mechanics of the skip and run. Once you and the clinician feel comfortable you will be asked to run down a runway approximately 10 meters in length and across a force platform. You will be asked to do this several times at differing speeds. Once you have completed several successful trials you will then skip down the runway and across the force platform several times. You will be videotaped during all trials to verify proper contact with the force platform.

Any information obtained in connection with this study that can be identified with you will remain confidential. The results of the research may be published in aggregate form with no identification given.

Your decision whether or not to participate will not prejudice your future relations with the University of Nevada, Las Vegas. You may withdraw from participation in this experiment at any time, but please inform the experimenter prior to withdrawal. If you have any questions please ask the experimenter. For questions regarding rights of human subjects, you may call the UNLV Office of Sponsored Programs at (702) 895-1357. Thank you for participating in this project.

Risks of Participation
Risks involved with this study are minimal. If you feel uncomfortable or at risk of injury during any running or skipping you are to stop immediately and the situation will be remedied.

Contact
Sam Johnson is the primary investigator for this study and can be contacted at (702) 895-4052.

Consent
I have read and understand the above information. I agree to participate in this study.

Subject's Signature ___________________________ Date __________

Investigator's Signature ___________________________ Date __________
APPENDIX C

APPROVAL FROM OFFICE OF SPONSORED PROJECTS
DATE: November 16, 1999

TO: Sam Johnson
Kinesiology
3034

FROM: Dr. William E. Schulze, Director
Office of Sponsored Programs (X1357)

RE: Status of Human Subject Protocol Entitled:
"Comparison of Ground Reaction Forces of Skipping and Running"
OSP #504s1199-162e

The protocol for the project referenced above has been reviewed by the Office of
Sponsored Programs and it has been determined that it meets the criteria for exemption
from full review by the UNLV human subjects Institutional Review Board. This protocol
is approved for a period of one year from the date of this notification and work on the
project may proceed.

Should the use of human subjects described in this protocol continue beyond a year from
the date of this notification, it will be necessary to request an extension.

If you have any questions regarding this information, please contact the Office of
Sponsored Programs at 895-1357.

cc: OSP File
APPENDIX D

SUBJECT QUESTIONNAIRE
Subject Questionnaire

Name ____________________________  Subject Number ________________
Age ______________  Sport __________________
Height __________________  Weight __________________

Are you currently suffering from any musculoskeletal injury?  YES       NO

Have you ever had a lower extremity ligament surgery?  YES       NO

Have you ever suffered from a lower extremity injury in which you received treatment for longer than seven days?  YES       NO
APPENDIX E

EXPERIMENTAL SET-UP
Instructions for skipping (adapted from Golden\textsuperscript{5} and Allerheiligen\textsuperscript{14}):

- In this study you will be taught how to form skip. This skill is also called form marching or A Drills. It will be taught in a progression from high knee marching to high knee marching with a skip.
- Begin by performing a high knee lift with the left leg.
- The left knee should be flexed so the left foot is level with the right knee, both horizontally and vertically. The foot should be cocked or dorsiflexed.
- The other leg should be fully extended, rising on the ball of the foot.
- Try this now.
- Your foot should contact the ground in the same cocked position landing on the mid-foot.
- Elbows should be flexed at about 90°
- The arm should be thought of as a pendulum with the shoulder as the pivot point.
- The arms should be moved through the range of motion in a snapping or punching action with the hands moving from shoulder level to the hip.
- The torso should be angled slightly forward to mimic a form seen with running.
- Try now combining the upper body with the form march.
- Once mastered on one leg, the other leg should be performed, progressing to continuous, alternating legs.
- Practice this now until you feel comfortable performing this for roughly 10 feet.
- Next you will add a small hop or skip to the drill.
- While skipping keep the foot is kept close to the ground.
- Try this now. Remember everything is the same as the form march but this has a skip added to it.
- Practice this skill down the runway until you feel comfortable.
| Condition | 1) | 2) | 3) | 4) | 5) | 6) | 7) | 8) | 9) | 10) | 11) | 12) | 13) | 14) | 15) | 16) | 17) | 18) | 19) | 20) | 21) | 22) | 23) | 24) | 25) | 26) | 27) | 28) | 29) | 30) |
|-----------|----|----|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
REFERENCES


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A Comparison of Ground Reaction Forces During Running and Form Skipping

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