

Skipping The Injuries: A Biomechanical and Metabolic Comparison Between Skipping & Running

By

Jessica Lynn McDonnell

April, 2016

Director of Thesis: (Paul DeVita)

Major Department: (Kinesiology)

Introduction: Benefits of aerobic exercise are apparent; the rising awareness has caused an increase in running participation and, an undeniable trend toward injury. The inherit injury risk associated with running calls for an alternate way to simultaneously achieve the benefits of aerobic exercise, while minimizing stress imparted on the body. Skipping presents an alternative movement pattern unique in its initiation and composition. Skipping is a voluntary decision, as opposed to a scaling progressing seen in the transition from walking to running and incorporates a double support, flight, and single limb support phase. We propose skipping to be an advantageous form of aerobic exercise, allowing a person to achieve increased training benefits with diminished risk of injury and subsequent reduction in training. **Objective:** This study has three related purposes aimed at describing, for the first time, how one skips. The first purpose compared basic gait characteristics; lower extremity kinematics and kinetics including ground reaction forces, joint torques, and powers in skipping and running. The second purpose investigated knee loads in skipping by comparing tibiofemoral and patellofemoral joint forces in skipping and running. The final purpose compared the metabolic cost of skipping to that of running. **Methods:** Twenty recreation active individuals mean age 21.5 (± 2) were recruited to complete a three day training program intended to familiarize participants with the skipping movement and testing environment. Training program consisted of cumulative 3 miles of skipping on three separate, not necessarily consecutive, days. Data collection employed a metabolic cart and treadmill to capture oxygen consumption in skipping and running. This was followed by randomized overground motion capture of the three conditions: skipping first leg (skip₁) second leg (skip₂) and running step (run). Speed was consistent 2.68 m/s across metabolic and biomechanical collections. Variables of interests were averaged across trials for each participant and mass normalized when applicable. One way ANOVA with repeated measures analyzed the biomechanical scores per variable per condition. Metabolic cost was compared with a dependent t- test between skipping and running. Scheffe post hoc test determined significant, alpha set to 0.05. **Results:** Not only are skipping and running significantly different from one another in kinetics, kinematics,

and metabolic parameters, the two steps of skipping differed significantly. Running displayed greater vertical ground reaction force peaks, larger maximal knee extensor torque values, higher peak negative power and work and greater peak maximal positive power at the knee, with average increase of 23% in knee compressive force as compared to skipping. Conversely, skipping had greater cadence, peak horizontal ground reaction force, maximum hip and ankle extensor torque, peak negative power and work, positive power at the ankle, a 27% greater metabolic cost and 36% greater caloric consumption. Between the two skipping steps skip₂ had the highest cadence, peak horizontal ground reaction force, maximum ankle extensor torque, peak negative power, work, and positive power. Each of the two skip steps have a separate function; skip₁ had predominately eccentric muscle functioned and acted to slow the body down, while skip₂ has a concentric bias in muscle activity and propelled the body forward into the next step. Evidence of this segregation can be seen in the distribution of the braking and propelling impulses.

Conclusions: Skipping and running present as significantly different movement methods. The decreased stride length associated with the skipping stride was correlated with the smaller knee compressive forces. The increased oxygen consumption needed to skip was in part explained by the nearly double vertical displacement of the center of mass. Further, the two alternating skipping steps that complete a stride made it unique from the one cyclical running step repeated in constant successive intervals. Skipping was temporally and spatially asymmetrical with successive foot falls partitioned into dominant functions, either braking or propelling the body. Thus, the energy saving methods proposed to be employed by tendons as they stretch and recoil may not be employed, creating a diminished energy return.

Skipping the Injuries: A Biomechanical and Metabolic Comparison Between Skipping &
Running

A Thesis

Presented To the Faculty of the Department of Kinesiology

East Carolina University

In Partial Fulfillment of the Requirements for the Masters of Science in Kinesiology:

Biomechanics Concentration

By

Thesis Author: Jessica McDonnell

April, 2016

© Jessica Lynn McDonnell, 2016

Skipping The Injuries: A Biomechanical and Metabolic Comparison Between Skipping & Running

by

Jessica McDonnell

APPROVED BY:

DIRECTOR OF
THESIS: _____

Paul DeVita, Ph.D)

COMMITTEE MEMBER: _____

(John Willson, Ph.D)

COMMITTEE MEMBER: _____

(Joseph Houmard, Ph.D)

COMMITTEE MEMBER: _____

(Kevin Zwetsloot, Ph.D)

CHAIR OF THE DEPARTMENT
OF KINESIOLOGY: _____

(Stacey Altman, JD)

DEAN OF THE
GRADUATE SCHOOL: _____

Paul J. Gemperline, PhD

Table of Contents

Title Page.....	i
Copyright page	ii
Signature page	iii
List of Tables.....	vii
Table 1	24
Table 2.....	25
Table 3.....	30
Table 4.....	35
List of Figures.....	viii
Figure 1.....	26
Figure 2.....	28
Figure 3.....	29
Figure 4.....	31
Figure 5.....	37
Figure 6.....	38
Figure 7.....	41
List of symbols / abbreviations.....	ix
Chapter I Introduction	1
Purpose	2
Chapter II Review of the literature	4
Kinematics	4
Running Kinematics	5
Skipping Kinematics.....	6
Kinetics.....	7
Running Kinetics	9
Skipping Kinetic	10
Modeling.....	10
Spring Mass Model.....	12
Metabolic Aspects of Locomotion.....	13
Running Metabolic Issues.....	15
Skipping Metabolic Issues	15
Running Injuries	15
Summary.....	16
Chapter III Methodology	17
Participants	17
Inclusion Criterion:.....	18
Exclusion Criterion:.....	18
Equipment.....	18

Procedures	19
Data Reduction	21
Statistical Analysis:	22
Chapter IV Results.....	24
Gait Analysis	24
Knee Joint Loads	28
Metabolic	30
Summary.....	30
Chapter V Discussion	32
Purpose One.....	32
Purpose Two	35
Purpose Three	39
Conclusion	42
References	43
APPENDIX A	47
Institutional Review Board Approval	47
Appendix B.....	48
Initial Phone Interview	48

List of Tables

Table 1: demographic data

Table 2: kinematic and kinetic variables of interest

Table 3: cumulative variables per kilometer

Table 4: knee and ankle range of motion

List of Figures

Figure 1: vertical and horizontal ground reaction force curves

Figure 2: torque and power curves

Figure 3: peak tibiofemoral and patellofemoral compressive force comparison

Figure 4: metabolic measurements

Figure 5: tibiofemoral compressive force and stride length correlation

Figure 6: patellofemoral compressive force and stride length correlation

Figure 7: oxygen consumption and vertical displacement correlation

List of symbols / abbreviations

Skip₁: initial skip step forward

Skip₂: second foot fall or hop

* indicates significant omnibus F test,

α indicates significant difference between skip₁ and run

β indicates significant difference between skip₂ and run

γ indicates significance difference between skip₁ and skip₂

Chapter I Introduction

A rising awareness of the multitude of benefits gained from aerobic exercise has led to an increase in the number of people running. Of those leading a healthy lifestyle, running is one of the most popular leisure sport activities. Industry surveys claim record numbers in participation with an overall growth of 70% in the past decade.¹ The expanding running population has been accompanied by a concurrent increase of chronic and acute running injuries.² The reported yearly incident of injury falls between 37 and 57% of all runners, with some claiming rates as high as 79%.^{2,3} The mechanics of running expose the body to high loads known to elicit overuse injuries at alarming rates.^{4,5} Injury often results in a reduction or cessation of training and subsequently, an attenuation of the health benefits gained.⁶ The ongoing injury trends in running call for an alternative way to simultaneously achieve the health benefits gained while mitigating the inherent risk of damage.

Running injury rates remain high and result in pain, injury, and unhealthy adaptations thereby creating further pain and injury that ultimately hinder exercise capability.⁵ The ability of one joint to compensate for the lack of support at another joint is evident.⁷ While specific mechanism of injury will vary, it is known that running mechanics produce large ground reaction forces. These forces are propagated proximally with the line of action being dictated by the joint angles modifying moment arms and influencing the degree of torque acting upon each joint. Running exhibits high torque values at the knee, escalating work done by the quadriceps thus, increasing strain through the patella tendon and applying pressure across the patellofemoral joint.⁸ Torque creates repetitive stress, triggering damage in ligaments, tendons, cartilage, and other connective tissue that act to stabilize associated joints. Continuous repetitive stress with insufficient recovery time will invariably leads to injury. Augmented stress or quantity of repetitions will produce greater trauma experienced and subsequently, injury.⁹

Skipping presents an alternative movement pattern that may reduce levels of stress imparted. Skipping is a gait observed most frequently among children, emerging developmentally after running and often around the age of seven.¹⁰ The stepping pattern is executed with a step (skip₁) and a hop (skip₂) on one leg followed by a step and a hop on the opposite leg. Skipping involves components of both walking and running seen by the double support, flight, and a single limb support phases. Skipping is considered a more stable movement pattern than running and has been used in the rehabilitative setting as a transition from walking to running post injury.¹¹ Johnson et al. found that at self-selected speeds, skipping produced a 20% reduction in ground reaction force magnitude compared to running.¹¹ Further research is warranted to more comprehensively understand the biomechanics of skipping and its potential as an alternate locomotion pattern.

Skipping has a substantially greater metabolic cost compared to running.^{12,13} Metabolic efficiency is the result of optimizing many variables; muscles performing work on center of mass, metabolic cost of generating force, and metabolic cost of performing work all contribute to the cost of locomotion.^{14,15} The metabolic cost of movement is proportional to the volume of active muscle and the rate of the force being generated.¹⁶ Biomechanical factors that contribute to substantial variations in movement economy are: vertical oscillation, stride length, change in velocity at ground contact, and peak magnitude in vertical ground reaction forces.¹⁶ Skipping exhibits substantial variations from running resulting in strikingly high metabolic demand.¹⁷ The greater metabolic demand needed to skip is a substantial benefit for individual looking to increase caloric expenditure.¹⁸

Purpose

The mechanics of running repeatedly expose the body to high loads. Torque generates strain through tendons, increases work done, further increasing tension, and applying greater

loads upon the joints. Injury rates range between 37 – 79% of runners reporting interruption to training yearly.^{3,19,20} While specific etiology of an injury continues to be discussed; continuous repetitive stress with insufficient recovery time will invariably lead to injury and result in cessation or reduction of training. The alarming injury rates call for an alternative way to achieve the health benefits gained from running while mitigating the risk.

Skipping presents with a single limb support phase, a double support phase, and a flight phase. The gait pattern is executed with a step and a hop on one leg followed by a step and a hop on the opposite leg. The kinematic and kinetic data on bilateral skipping is incomplete. To my knowledge, no studies have been conducted examining the biomechanical and metabolic differences between skipping and running. The present study has three related purposes. The first purpose will compare basic gait characteristics; lower extremity kinematics and kinetics including ground reaction forces, joint torques, and powers in skipping and running. The second purpose will investigate the knee loads in skipping by comparing tibiofemoral and patellofemoral joint forces in skipping and running. The final purpose will compare the metabolic cost of skipping to that of running.

Chapter II Review of the literature

The intent of this study is to investigate the biomechanics of skipping as compared to running. The first purpose was to compare basic gait characteristics; lower extremity kinematics and kinetics including ground reaction forces, joint torques, and powers in skipping and running. The second purpose is to investigate the knee loads in skipping by comparing tibiofemoral and patellofemoral joint forces in skipping and running. The final purpose will compare the metabolic cost of skipping to that of running. This chapter will review the literature within these parameters to better understand previous findings.

Kinematics

Kinematics describe the motion of joints or body segments without regard to time or cause of movement by evaluating the trajectory of points and lines.²¹ The human body is traditionally thought of as a series of segments, assumed to be rigid bodies, linked by frictionless hinge joints.²² Rigid bodies are described by orientation and location of a predetermined point on the body within the global system, defined as the laboratory, and the local reference system, attached to the body.²¹ Linked segments connected by joints form a kinetic chain that possess directional conditions: distal and proximal with orientated toward the bodies center or in reference to a specified locality. Based on this convention, human body position is defined using: location, orientation, and joint configuration parameters.²¹ The state of the system can be further discussed using generalized coordinates, a measurement that characterizes the independent coordinates that specify the state of a system. This measurement concerns the degrees of freedom that define the way a body can move. The number of degrees of freedom a body of interest possesses determines how, and in which direction, movement is possible based on the number of links and types of joints. Joints that can move about multiple planes have more degrees of freedom. The total number of degrees of freedom in a kinematic chain is expressed

by its mobility and calculated using Gruebler's formula, $F = 6(N - k) + \sum_{i=1}^k f_i$ where N is the number of links, k is the number of joints, and f_i is the number of degrees of freedom in the i th joint.²¹

Planar kinematics can be employed when the motion plane is known and the reference planes are positioned strictly parallel to the plane of the articular motion. If a plane is incorrectly identified there is kinematic cross talk and error is propagated.²¹ The position and orientation of a rigid body in space is defined by three components of translation and three components of rotation for a cumulative six possible degrees of freedom. Lower extremity motion occurs in precise synchronization in relation to the rest of the body and world, kinematics describe the movement.²²

Running Kinematics

Running is a cyclical movement executed within a typical movement pattern range. The gait can be sectioned into contact and flight phases' coinciding with the periods of time the runner is in contact and not in contact with the ground.²³ At the beginning and end of each flight phase there is a period of double-float, where neither limb is in contact with the ground. The contact phase can be divided into absorption and propulsion phases based on muscle activity and function. The foot rapidly dorsiflexed at initial contact in conjunction to hip and knee flexion. The propulsion phase commences with initial extension of the knee and ankle.²⁴ The knee is slightly flexed for the majority of the stance phase with initial eccentric activity. Ankle plantar flexors have a plantar flexor moment and provide lower leg stabilization.^{7,25} An increase in velocity is accompanied by a lower center of gravity typically obtained with increased hip, knee, and ankle flexion. Support during stance is primarily achieved by a net extensor pattern of

moments at the hip, particularly during the initial portion of stance.⁷ Each leg completes two contact and flight phases to form a complete stride.²⁴

Further descriptive measures of gait incorporate stride length, step length, and cadence. Stride length defines the distance from the initial contact of one foot to the initial contact of the contralateral foot. Step length is the distance traveled through a single gait cycle, from initial contact of one foot to initial contact of the same foot. Cadence explains the number of steps taken in a unit time.²⁴ Velocity alters the rate at which events occur as well as the joint range of motion used to complete motion.

Skipping Kinematics

Humans chose to switch from a walk to a run at speeds near 2 m/s to enhance the biomechanical performance of the ankle plantar flexors and to improve coordination of the knee and ankle muscle during stance.²⁶ Skipping, alternatively, is the result of pushing the walking gait to unnaturally high speeds.¹² The gait pattern exhibits components similar to both walking and running with a single and double contact phase as well as a single and double flight phase. Skipping is a unique rhythmic, symmetrical gait with two ipsilateral footfalls. There is a single step forward (skip₁) and a hop on the same foot (skip₂), followed by a step forward and hop on the opposite foot to complete the stride. Landing from the hop occurs at the balls of the foot and ideally the heel does not touch down before the weight is transferred to the other foot. The arms act opposite and synchronously with the stepping leg.^{10,27} The double support present in skipping is thought to increase stability and enable a participant to self-regulate force distribution between legs during impact without gross observational compensation patterns. This feature has led to the utilization of skipping in the rehabilitation setting as a means of progressing lower extremities injuries to running.¹¹

Kinetics

Kinetics concern the causes of motion. Forces acting on the body of interest are either internal or external, and influence the linear or angular motion of a body by changing the body's linear or angular momentum. Forces change the mechanical energy of a body by increasing it and performing positive work, or by reducing it and performing negative work.²² External measurements are composed of ground reaction forces whereas internal forces include those acting on joint surfaces and those produced by muscles acting on tendons with some contribution from other soft tissues.²⁸ Muscle forces further contribute to joint forces. Kinetic measurements provide valuable insight into the net effect of all agonist and antagonist muscle activities.⁷

Ground reaction forces are the summation of the body weight and all external forces for accelerating or decelerating the body mass. During the contact phase of gait ground reaction forces are exerted by the ground on to the foot and propagated proximally along the kinetic chain. There is a vertical, horizontal and transverse component of the ground reaction force. Loading rate, impact peak, relative minimum, thrust maximum, decay rate are all used to describe the shape and pattern of the ground reaction force. These factors are influenced by external factors such as an individual's body mass, foot strike pattern, and speed.²⁹ The vertical component is typically the largest in magnitude. The horizontal force vector is generally biphasic corresponding with the initial deceleration and propulsion portion of the contact phase. The braking force occurs with initial contact and when ground reaction force direction opposes forward movement. The propulsion portion begins when the force is consistent with the direction of forward motion.³⁰ Transverse ground reaction forces are relatively small by comparison and have been characterized by their large variance. The active portion of the ground reaction force is produced via activated leg extensor muscles, which are successively stretched and shortened.²³ Both vertical and horizontal forces are a reflection of the total mass-

acceleration product of all body segments and represent the net muscle and gravitational forces acting throughout the contact phase. The body responds to the imposed forces by synchronizing isometric, concentric, and eccentric muscle activity in such a way to produce movement and maintain posture.

The resultant force vectors point of application and its subsequent line of action, determines angular motion. Rotation is induced when a force vector passes a distance from the axis of rotation. The displacement of the force, defined from the axis of rotation to the point of application, creates the moment of force. The perpendicular distance from the axis of rotation to the force line of action is known as the moment arm.²² The product of the magnitude of the force and length of the moment arm determines of the torque value. The term torque is used when there are multiple force vectors or points of application, such as when considering the complex interaction between the structural and material properties of the linked segment system.

Torque at a joint is the net effect of all tissue across a joint; the summation of total force vectors distributed across a joint surface.⁴ Support torque is a measurement of the net total torque during stance by all three of the joints of the lower limb: hip, knee, and ankle.²⁸ Isolating exact individual contributions presumes too much. Thus, a model, as a simplification of reality is used to infer torques and compressive forces acting on the joint.

Work done on a body by a body quantifies the changes in mechanical energy. Work is a calculation of the work done by the resultant forces, moments of force, or the total external, internal, and total work accomplished. The rate of doing work is measured in power. Normal conventions designate positive power when energy is generated through concentric muscle active and negative when energy is absorbed through eccentric muscle activity, or elongation of

soft tissue.³¹ The time integral of power curves at each joint signifies work done.³² These calculations aid in the establishment of the accomplished sequence of muscle forces.

Running Kinetics

Ground reaction forces are transmitted throughout the stance phase with a typical double peak curve configuration for the vertical component.²³ Initial impact peak is followed by a decrease and a subsequent rise to a second peak at mid-stance. The decay rate describes the rate the force tapers as the contact phase approaches termination.³⁰ All components of the ground reaction force are directly influenced by speed.²⁹ Increases in running speed are accomplished via increase in stride length and/or frequency.³³ Increase in stride length tends to place the center of gravity farther behind the point of ground contact resulting in a larger horizontal ground reaction force.

The contact portion of the running gait cycle comprises 50% or less of the stride with variations due to changes in velocity.²⁴ There is typically a single plantar flexor peak, with some variation depending on foot strike pattern. Knee moments are primarily composed of a single extensor peak, with a flexion portion slowing the leg just prior to ground contact. Hip moment predominantly consists of an extensor torque through the contact phase with a conversion to flexion as the limb transitions into flight phase and the limb swings forward with an extensor action to slow the thigh prior to contact.²² Muscle action can be appropriately divided into two main phases based on power curves, with the initial portion of the contact phase exhibiting a period of net negative work in the knee and ankle joints and the final portion exhibits a period of net positive work.²³ The support torque is consistently positive, indicating the extensor direction, during stance portion of gait at the muscle are predominantly extending versus the negative net support moment during swing when the lower extremity exhibits more flexion.³⁴ Net muscle

moments at the ankle, knee, and hip joints are much smaller during the swing phase than during the stance phase.³⁵

Skipping Kinetic

The skipping pattern presents with altered step rate and limb position as compared to running.¹¹ Skipping exhibits an increased stride frequency compared to running at all speeds and gradients.¹³ The altered stride pattern and limb position throughout the stride influences the loading and decay rate, impact peak, relative minimum, and thrust maximum.²⁹ A ten percent or greater increase in step rate, with constant speed, reduces impact load on the body via decreases in the force magnitude transmitted along the kinetic chain.³³ The manifestation of the altered step rate is in some measure expressed by the decreases in ground reaction forces when comparing skipping and running at self-selected speeds.¹¹ The decreased magnitude in the ground reaction forces transmitted offloads the knee and can potentially spare cartilage from potentially damaging loading.³⁶ By assuming the force vector line of action passes through or near the center of mass a large extensor torque can be expected to be generated at the hip and ankle joints throughout contact phase.³⁷ A pattern of shorter stride length accomplished with a decreased hip range of motion and increased knee flexion results in a greater work and positive peak power performed at the hip and increased negative work and peak power performed the knee.¹⁴

Modeling

Computational modeling, in conjunction with gait measurements, is essential to describe and explain muscle and joint function in human locomotion.²⁶ Musculoskeletal function results from complex neurological, muscular, and skeletal interaction.³⁸ To determine at any instant which muscles are acting at what magnitude cannot be stated with absolute certainty, as joints are encompassed by several muscles and connective tissue. A net joint moment can be produced

by a number of muscle recruitment solutions.³⁹ Inverse dynamics are used to solve for the unknown forces and torques with measured motion. Forces acting directly on the body of interest are summed. Muscle-force calculations are not significantly influenced by the inclusion of either muscle activation dynamics or a time dependent performance criterion.⁴⁰ Estimated calculations from inverse and forward dynamic methods can be influenced by the performance criterion assumed, errors obtained in tracking biomechanical gait data, and the inclusion of muscle activation dynamics in the formulation of the optimization problem.³⁹ It is preferable to start inverse dynamic calculations at the foot and move proximal as the mass of the foot is small and thus, there is less error propagated.⁴¹ Errors in calculations come from noisy data, inertial properties, and the acceleration data, which is derived from the position data that is susceptible to soft tissue artifacts that in turn can result in incorrect description of movement.⁴²

The model applied in the present study uses lower extremity joint forces and moments calculated from inverse dynamics and the kinematics of lower extremity and relevant anatomical and physiological characteristics to calculate forces produced by the quadriceps, hamstring, gastrocnemius and lateral soft tissue support structures. Net forces are combined with the knee joint reaction forces to quantify the compressive and shear forces acting at the tibiofemoral joint.⁴³ The plantar flexor moment during the contact portion of gait is derived for each ankle position based on normative values in the literature.⁴⁴ The resulting force vector is assigned a direction based on the heel and knee marker positions. Hamstring force is calculated from the extensor moment at the hip, assumed to be produced by the hamstrings and gluteus maximus with no co-contraction of the hip flexors during the initial half of the contact phase. The quadriceps force is calculated from the observed net knee joint torque and hamstring and gastrocnemius forces, appropriately accounting from co-contracting knee flexors. Normative

values from the literature were used to determine the appropriate moment arms acting at the knee throughout the contact portion of the gait cycle.⁴⁵ The distribution of frontal plane loads, specifically the force in the lateral support structures at the knee through the contact phase, is the product of a critical interaction between dynamic muscle forces and forces in the passive soft tissue necessary for stability during movement. The external loads imposed by an adductor moment on the knee are resisted by a conjunction of abductor moments from the quadriceps and the lateral soft tissue support. The quadriceps abductor moment is subtracted from the observed net internal abductor moment calculated in inverse dynamics. The remaining moment is distributed to the lateral knee tissues.⁴⁶ Force in the tissues is calculated as the quotient of the torque and moment arm. Knee joint forces are a summation of all the forces assumed to acting upon the joint calculated by the force in the lateral support structures and the joint reaction forces identified with inverse dynamics partitioned in to their compressive and antero-posterior shear components and summed. The equations are as follows:

$$Ks = G \sin \alpha - H \sin \beta + Q \sin \Phi - Kz \sin \lambda + Ky \cos \lambda$$

$$Kc = G \cos \alpha + H \cos \beta + Q \cos \Phi - Kz \cos \lambda + Ky \sin \lambda + Lss$$

Where Ks and Kc are the shear and compressive forces at the knee, Kz and Ky represent the vertical and horizontal knee joint reaction forces and Lss is the force in the lateral support structures. Ks is positive when the shear forces applied and anterior load to the tibia and Kc was positive when the compressive force pushed into the tibia.⁴³

Spring Mass Model

Analyses of joint work and power are an indirect measure of muscle-tendon function.³⁷ A muscles will stretch or shorten to produces force and perform work on the center of mass; swing the legs relative to the center of mass, and support body weight. Tendons consequently experience a change in length corresponding with their associated muscle movement and

translate the force on to the bone in order to reposition.³⁵ A tendon's primary function is to transmit force on bone, requiring tendons to be relatively stiff and strong in tension. This structural property allows tendons to store and release energy. In an event such as initial contact, tendons are stretched and the energy associated with decelerating mass is stored within tendons as elastic strain energy.³⁵ Throughout ground contact a tendon will cyclically store and release mechanical energy; accelerating of the body in the upward and forward direction. Elastic properties of the 'linear leg spring' are characterized by legs stiffness: ratio of the peak force to the maximum compression of spring, an increased angle swept by the leg spring, and vertical displacement of center of mass.⁴⁷

Metabolic Aspects of Locomotion

Muscles transform metabolic energy into force. Force is a product of tension, which indirectly produces movement via, cross bridge formation requiring substantial amounts of ATP.⁴⁸ Submaximal rate of oxygen consumption provides a good measure of the metabolic energy consumption. Net metabolic power represents a normalized measurement.⁴⁹ The cost of locomotion calculates the amount of work needed to walk per unit mass and distance.¹³

$VO_2Task - \{[(VO_2 standing \times 1000)(\frac{20.1}{mass})]/walking speed\}$ with 20.1 being the cost of locomotion and the gross metabolic power is the rate of work per unit mass:

gross metabolic energy cost/distance (J/kgm)

Net metabolic power is calculated by subtracting the gross metabolic power of standing from the gross metabolic power of the task.⁴⁹ The rate of metabolic energy consumption in recreational level activity increases linearly when the primary energy source is provided aerobically.⁴⁷

Muscle function determines the cost of the action. Movement is produced through a combination of internal and external forces: movement of limbs relative to the whole body center

of mass or movement of the whole body's center of mass relative to the ground.⁴⁷ The most prominent consideration when evaluating the metabolic cost of activity are the levels of contraction necessary to support body weight, perform work to redirect and accelerate the center of mass, and maintain stability. Isolated influence of individual tasks is used to gauge the amount of work required to lift and accelerate the center of mass, perform external and internal work, and maintain stability.¹⁵ Each aspect individually contributes to the gross cost of transport. The cost of performing work is nearly twice the cost of generating force.¹⁵ Load carrying increases the demands on muscles, requiring more activation in order to support the greater weight and redirect and move the greater mass. This has been shown by the more than direct proportion between energy consumption and added loads. The cost of performing work to redirect and accelerate the center of mass is calculated as the ratio of change in net metabolic cost due to added mass alone to the change in net metabolic cost due to added weight and mass show that the work done to redirect and accelerate mass comprises about half the cost.¹⁵ The cost of generating force throughout contact is dependent on the magnitude and rate of muscle force generation.³⁵ During the propulsive portion of the contact phase the tendons recoil, releasing stored elastic strain energy.⁴⁸ This cyclical pattern of storing and releasing energy has been proposed as a mechanism for reducing the total amount of metabolic energy expended during locomotion.⁵⁰ An isometric contraction consumes more metabolic energy than an eccentric contraction and less metabolic energy than a concentric contraction normalized to force output per fiber.⁴⁸ Ultimately, the cost of transport is an optimization of many factors and a function of the cumulative metabolic rates of the muscles that produce locomotion and maintain stability.⁵¹ As muscle systems develop habitual optimal economy and neurological control of the desired motion, there is a reduced cost of activity and therefore a decreased imposed demand

upon the body, and diminishes training benefits.⁵² Measure of metabolic cost represent energy usage and training benefits obtainable.

Running Metabolic Issues

Positive work done at the hip and ankle has been directly related to metabolic power values. Greater negative joint work at the hip, greater positive joint work at the knee, and lower negative joint work the ankle are correlated with lower metabolic cost.^{53,54}

Skipping Metabolic Issues

The progression from walking to running occurs at a certain speed for convenience, comfort, efficiency, and economy. Dissimilarly, skipping is a voluntary decision as opposed to a scaling succession.⁵⁵ Hopping in animals presents with a unique energy demand and has been associated with the gravitational potential energy and the horizontal component of the external kinetic energy. Each of these forms of mechanical energy is decreased with impact (braking) and is increased with the subsequent take-off (propulsion). The lengthening phase of ankle extensors coincides with the impact phase and the shortening phase coincided with takeoff. Suggesting that elastic strain energy is stored during impact, followed by the energy release from these tendons during take-off may save metabolic energy.⁴⁸ However, the metabolic impact on the gross displacement of the center of mass as well as the altered stride length associated with skipping appears to increase with exasperated movement.¹⁴ Interestingly, the typical relationship between increased gradients or speeds, and increased metabolic cost is not found to be true with skipping. There is actually a decreased metabolic cost with the increase in speed or gradients, a feature only else seen in jumping kangaroos.¹³

Running Injuries

A reported 56 percent of recreational runners will sustain a running related injury each year.³³ Sustained injuries have been correlated to the high forces and positive power occurring

during the propulsion phase.⁵⁶ Running participant's Achilles tendon, ankle joint, lower leg, patellofemoral joint, patellar tendon, and plantar fascia are loaded several times the body weight throughout the running cycle.²⁰ Running exhibits tremendous peak ground reaction forces and has been postulated to contribute to the pain and injury associated with this locomotion pattern.⁵⁷ Running injuries are often classified as 'overuse' indicating that the accumulation of stress over time results in biological reactions that hinders the maximal stress a structure can sustain without failure.³³ The alterations in the movement pattern between skipping and running tentatively suggest that the increase in stride frequency decreases the ground reaction forces would decrease the torque at the joints and subsequently decreasing compressive loads and reducing stress imposed on the soft tissue throughout movement.

Summary

The two gaits, running and skipping, vary in their kinematic, kinetic, and metabolic parameters. Based on information available, skipping as a form of locomotion presents an alternate gait pattern with lower ground reaction forces and a higher metabolic cost. The manifestations of these changes will be observed using the methods described in the following chapter.

Chapter III Methodology

The study examined the differences in locomotion biomechanics, internal knee joint loads and metabolic cost between skipping and running. The purpose of the study was to compare skipping and running by quantifying the lower extremity joint torques, powers, ground reaction forces, knee loads, and metabolic cost. The general procedures for the study will be outlined in the following section. The testing was conducted at the East Carolina University Biomechanics Laboratory and consisted of a period of training prior to testing to ensure consistency of technique. Kinematic, kinetic, and metabolic data was collected and analyzed to determine the differences between the two gaits.

Participants

Participants were recruited from the East Carolina University student body, staff, and the citizens of Greenville, NC. Methods of recruitment included the use of fliers, classroom announcements, newspaper ads, email and advertisements on the laboratory website. Interested individuals were screened to ensure they meet all inclusion criteria. Twenty recreationally active individuals were selected to participate in the study protocol, with rolling admission. Selected participants were between the ages of 18 and 30. Additional criterion required the participants to be healthy and mobile with no current or lingering musculoskeletal injuries whom regularly participated in physical activity three days a week free of pain. They had a body mass index less than or equal to 28 kg/m^2 and were able to complete the training program. Participants could not smoke cigarettes, have a diagnosis of cardiovascular, pulmonary, neurological or other major diseases that would affect their ability to aptly perform required tasks. The protocol was approved by the East Carolina University Institutional Review Board (Appendix A) and all participants signed an informed consent prior to participation.

Inclusion Criterion:

1. Between the ages of 18 and 30
2. Healthy and mobile with no current or lingering musculoskeletal injuries or conditions of the lower extremity
3. Regularly participation in physical activity 3 times a week
4. Free of pain or difficulty with exercise
5. Body mass index of less than or equal to 28 kg/m^2
6. Signed written informed consent
7. Completed training program

Exclusion Criterion:

1. Present chronic or acute injury
2. Present illness or suffering from cardiovascular, pulmonary, neurological or other major diseases that would affect participant's ability to aptly perform tasks
3. Regular smoking of the cigarettes, cigars, or any form of tobacco

Equipment

Skipping and running trials were collected in the East Carolina University Biomechanics Laboratory. Kinematic data was captured using 8 Qualisys ProReflex MCU 240 cameras (Qualisys Medical AB, Gothenburg, Sweden) at 120 Hz. The cameras were arranged in a circular configuration, approximately 1.8 meters from the center of the collection volume. Ground reaction force data was measured using an in ground force platform (AMTI Model LG-6, Newton, Ma) located at the approximate center of the volume and collected at a frequency of 960 Hz and 4000 amp gains for all trials. Six channels were used to collect the three dimensional forces and moments acting on the plate. Gait speeds were regulated using infrared timing system (Brower timing systems, model IRD-T175, Salt Lake City, Utah). All data was collected with Qualisys Track Manager Software (Innovision Systems Inc., Columbiaville, MI) and analyzed using Visual 3D (C-Motion Inc., Rockville, MD). Data from all participants was compiled and group means were calculated using Visual 3D software. All participants' height and weight was determined in the metric system using a Seca 703 digital scale (Seca gmbn & C.

Kg, Hamburg, Germany). Metabolic data was collected using the metabolic measurement system (trueone2400, parvo medics, Sandy, UT) participants performed each locomotion pattern for six minutes at 2.67 m/s (6 mph) on the life fitness 95 ti treadmill.⁵⁸ Data was collected for the full six minutes with the final two minutes of data averaged for analysis. Participants had a minimum rest period of 10 minutes between trials. Equipment was calibrated and maintained in accordance with factory protocol.

Procedures

Subject recruitment was accomplished by distributing fliers across the ECU campus and classroom announcements. Initial interview was completed over the phone in order to gather participants' demographic information, pertinent past and present medical history, and to briefly explained the study procedure. The interview questionnaire is located in Appendix B. If subject was eligible and interested he/she was scheduled for an initial meeting where informed consent was signed and the procedure explained in full detail. If interested and eligible they would complete the first training session that day. Training consisted of three separate sessions prior to a final data collection. The initial over ground skipping session totaled a mile with no emphasis on speed or regulated breaks. This format was intended to familiarize participants with the motion pattern at their leisure and comfort. The subsequent two training sessions were completed on a lab treadmill expected to familiarize participants with treadmill skipping at test speeds and conditions. The second training session was non-consecutive, cumulative mile with the goal to reach test speeds for a minimum distance of ¼ mile. The third session was separated into two ½ miles; with the second half mile completed at test speeds with the metabolic mask on. Upon completion of the training program participants had completed a cumulative three miles of skipping and returned for a final session to collect the data. The entire program was completed within two week from informed consent to data collection. Subject's height and weight were

recorded on the day of collection. Metabolic data was collected first. A two minute standing calibration was obtained followed by a minimum of two minutes of walking to ensure the mask was properly fitted. Participants then either ran or skipped for four minutes prior to a two-minute collection reflecting steady state movement. The order of these tasks: run / skip was randomized with a minimum of ten minutes rest before procedures were repeated, sans the calibration, for the other condition. A rest period in which participant changed into tight fitting clothing and prepped for motion capture collection preceded the overground trials needed to collect the unilateral kinematic and kinetic data. Reflective markers were adhered to the participant to identify the body segments and joint centers. Location of the markers followed the modified Helen Hayes marker set: right and left posterior superior iliac spine (PSIS), right and left iliac crest, right and left anterior superior iliac spine (ASIS), right and left greater trochanter, right medial and lateral knee, right medial and lateral malleoli, right heel, right first and fifth metatarsal heads, a thigh plate consisting of four markers was placed on the lateral side of the right thigh, a shank plate consisted of four markers placed on the lateral side of the right leg, and a foot plate with three markers (two lateral one medial) was placed on the superior side of the right foot. A four second calibration was taken where the participant stands completely still with arms folded across their chest so no markers were blocked by the arms. After the calibration trial the iliac crest, greater trochanters, knee, malleoli, and metatarsal head markers were removed.

Data collection trials were completed at 2.68 m/s ($\pm 5\%$). An acceptable trial exhibited a consistent stride, unaltered to achieve complete foot fall on the force plate. Participants performed five successful trials for each condition: run and skip (lead foot contact, skip₁ and trail foot contact, skip₂). Speed was regulated using infrared timing gates. Order of conditions was randomized.

Data Reduction

Data collected from each subject was processed with Qualisys Track Manager Software. Position data from each subject and their respective trials was evaluated in the global coordinate system. Visual 3D used inverse dynamics to calculate joint torque and power at the hip knee and ankle. The first recorded calibration trial was used to create an individualized unilateral model for each subject. The linked rigid-segment system model enabled location of the joint centers, segment center of mass, defined the local coordinate system of each segment, and calculated a transformation matrix to determine the location of the reflective markers within the global coordinate system. Joint centers were located by calculating fifty percent of the distance between the medial and lateral calibration markers for each joint. The hip joint was calculated to be twenty-five percent of the distance between the markers identifying the right and left greater trochanters. A line from the proximal joint center to the distal joint center, defined each segment's long axis. Anthropometrics were used to locate each segment's center of mass from the proximal joint center. Initial toe off, initial heel strike, and final toe off event markers were identified and labeled in visual 3D. Step length was defined as the distance between initial toe off before the plate to toe off after the plate.

Joint kinetics were calculated by shifting ground reaction forces and torques, center of pressure, force on the segment due to gravity, segment center of mass accelerations, proximal and distal moment arms, and proximal and distal joint center location into the local coordinate system of each segment. A free body diagram was used to calculate vertical and horizontal joint reaction forces and coinciding joint torque for each lower extremity joint. The values were calculated using inverse dynamics beginning with the foot segment, as that is the segment in contact with the force plate from which the external force is measured. Once found, the process was repeated for each segment in the order of: shank, thigh, and hip. Inverse dynamics used

linear and angular Newtonian equations of motion and applied equations to the rigid segment model of the lower extremity: thigh, shank, and foot. Joint reaction forces and torques were calculated from the measured ground reaction forces, center of pressure, standardized segment anthropometrics, and the kinematic position and acceleration data. Joint powers were calculated as the product of joint torques and joint angular velocities. Visual 3D software was used to calculate the joint reaction forces, joint torques, and joint powers. Maximum joint torques and powers at the hip, knee, and ankle were derived from these data.

Knee joint, including tibiofemoral and patellofemoral compressive forces, were derived with a musculoskeletal model of the lower extremity. The equations in the model and the overall approach are described in detail⁴³ and the model has been used in both walking and running gaits previously.^{60,61} The model used lower extremity joint forces and moments calculated with inverse dynamics along with the kinematics of the lower extremity and related anatomical and physiological characteristics to calculate forces in the three largest knee muscles and in the lateral soft tissue support structures (e.g. lateral collateral ligament). These forces are then combined with the knee joint reaction forces to determine the tibiofemoral and patellofemoral compressive forces. Maximum and cumulative tibiofemoral and patellofemoral forces were derived from these data.

Statistical Analysis:

The maximum joint torques and powers, maximum vertical and horizontal ground reaction forces, maximum knee joint forces and stride length in running and the two different steps in skipping were averaged across trials for each participant. The average values were entered into statistical analyses. A one way , repeated measures, analysis of variance was used to analyze the twenty biomechanical scores per variable per condition. The three conditions were

skipping-first step (skip₁), skipping-second step (skip₂) and running (run). Scheffe post hoc tests were used to determine specific differences in the case of a significant F-test. Alpha was set to 0.05 for all analyses. Oxygen consumption was compared between running and skipping gaits with dependent t-test and alpha <0.05.

Chapter IV Results

In fulfillment of the study's intent to contribute to the minimal body of knowledge on bilateral skipping and examine an alternate form of locomotion; a lower extremity gait analysis was performed to examine both steps in skipping as compared to each other, and running. A comparison of kinematics, kinetics, and metabolic parameters are reported. Results will be presented for each skipping step (identified as skip₁ and skip₂) and for the single running step (identified as run). Skip₁ was operationally defined as the initial step forward with skip₂ being the subsequent hop on the same foot. Demographics are displayed in Table 1.

Table 1: mean (\pm sd) demographic data

Demographics	
Sex	10 F; 10 M
Age (yrs)	21.5 (\pm 2)
BMI (kg/m ²)	23.3 (\pm 2.5)

Gait Analysis

The differences within the skipping steps and between skipping and running are in part demonstrated by the significant difference in the velocity and stride length [Table 2]. Skip₁ had both the fastest and longest step, being 7% faster and 17% longer than the run step ($p < 0.001$) and 33% faster and 65% longer than skip₂ ($p < 0.001$). Skip₂ was the slowest and shortest step, 28% shorter and 58% as slower than run. These differences were manifested in the cadence calculations with skip₁ averaging 138 (\pm 17) steps per minute and skip₂ 259 (\pm 30) steps/min. Run averaged 151 steps/min, a 24% decline. The two skip steps had a 45% increase in vertical displacement compared to run [Table 2].

Table 2: mean (\pm sd) stride kinematics, ground reaction force (GRF) joint torque parameters, power and work broken up into early and late phases of stance for the total limb, knee, and ankle. $^{\alpha\beta\gamma}$

Variable of Interest	Run	Skip ₁	Skip ₂
Velocity(m/s)*	2.78 (\pm 0.22) $^{\alpha\beta}$	2.98 (\pm 0.18) $^{\gamma}$	1.99 (\pm 0.18)
Stride Length(m)*	2.21 (\pm 0.17) $^{\alpha\beta}$	2.68 (\pm 0.29) $^{\gamma}$	0.93 (\pm 0.15)
Cadence(steps/min)*	151 (\pm 9) $^{\alpha\beta}$	138 (\pm 17) $^{\gamma}$	259 (\pm 30)
Change Vertical Position (m)*	0.111 (\pm 0.02) $^{\alpha\beta}$	0.201(\pm 0.03)	0.201 (\pm 0.03)
Peak Vertical GRF(N/kg)*	23.72(\pm 1.80) $^{\alpha}$	22.66 (\pm 1.67)	23.02(\pm 2.76)
Peak Horizontal Braking GRF(N/kg)*	-2.91 (\pm 0.50) $^{\alpha\beta}$	-3.83 (\pm 0.55) $^{\gamma}$	-5.31 (\pm 1.22)
Braking Impulse (Ns/kg) *	-0.21 (\pm 0.04) $^{\alpha\beta}$	-0.40 (\pm 0.07) $^{\gamma}$	-0.11 (\pm 0.03)
Peak Horizontal Propelling GRF(N/kg)*	2.57 (\pm 0.32) $^{\alpha\beta}$	1.19 (\pm 0.35) $^{\gamma}$	5.00 (\pm 0.61)
Propel Impulse (Ns/kg)*	0.19 (\pm 0.3) $^{\alpha\beta}$	0.05 (\pm 0.02) $^{\gamma}$	0.47 (\pm 0.06)
GRF Resultant Impulse (Ns/kg/km)*	1698 (\pm 154)	1837 (\pm 142)	1837 (\pm 142)
Peak Hip Extensor Torque(Nm/kg) *	0.82(\pm 0.25) $^{\alpha\beta}$	1.54 (\pm 0.22) $^{\gamma}$	0.35 (\pm 0.27)
Peak Knee Extensor Torque(Nm/kg) *	2.83(\pm 0.40) $^{\alpha\beta}$	2.45(\pm 0.50) $^{\gamma}$	1.34 (\pm 0.81)
Peak Ankle Extensor Torque(Nm/kg) *	2.54 (\pm 0.32) $^{\alpha\beta}$	2.16 (\pm 0.28) $^{\gamma}$	2.97 (\pm 0.42)
Support Phase Total Work	-0.08 (\pm 0.24) $^{\alpha\beta}$	0.52 (\pm 0.37) $^{\gamma}$	-0.46 (\pm 0.36)
Negative Work -contact phase (J/kg) *	-1.56 (\pm 0.22) $^{\alpha}$	-0.95 (\pm 0.24) $^{\gamma}$	-1.48 (\pm 0.49)
Positive Work -contact phase (J/kg) *	1.48 (\pm 0.22) $^{\beta}$	1.47 (\pm 0.36) $^{\gamma}$	1.02 (\pm 0.28)
Knee			
Peak Negative Power -early stance (W/kg) *	-9.78 (\pm 1.79) $^{\alpha}$	-5.39(\pm 1.66) $^{\gamma}$	-4.21 (\pm 3.29)
Work -early stance (J/kg) *	-0.62(\pm 0.14) $^{\alpha\beta}$	-0.29 (\pm 0.11)	-0.24 (\pm 0.23)
Peak Positive Power (W/kg) *	5.84(\pm 1.36) $^{\beta}$	5.50 (\pm 1.83) $^{\gamma}$	1.69 (\pm 1.72)
Positive Work (J/kg) *	0.38(\pm 0.11) $^{\beta}$	0.35 (\pm 0.15) $^{\gamma}$	0.08(\pm 0.10)
Ankle			
Peak Negative Power -early stance (W/kg) *	-6.13(\pm 1.58) $^{\alpha\beta}$	-3.73 (\pm 0.96) $^{\gamma}$	-10.44 (\pm 3.32)
Work -early stance(J/kg) *	-0.42(\pm 0.15) $^{\alpha\beta}$	-0.22 (\pm 0.07) $^{\gamma}$	-0.72 (\pm 0.25)
Peak Positive Power (W/kg) *	9.75 (\pm 1.97) $^{\alpha}$	8.38(\pm 2.05) $^{\gamma}$	10.18 (\pm 2.82)
Positive Work (J/kg) *	0.68 (\pm 0.13) $^{\alpha}$	0.54 (\pm 0.16) $^{\gamma}$	0.64 (\pm 0.19)

* denotes a significant omnibus F test, α indicates significant difference between skip₁ and run, β indicates significant between skip₂ and run, γ indicates significance between skip₁ and skip₂, all tests significant at $p < 0.05$

Maximum vertical ground reaction force values for the 3 steps are displayed in Table 2 with curves depicted in Figure 1. Running had a 5% higher peak vertical force value compared to skip₁ ($p < 0.009$) but was statistically identical to skip₂. The maximum braking ground reaction

force presented greater variability in that all three steps were significantly different ($p < 0.001$). Skip₂ had the largest value, 28% greater than skip₁ and 45% more than run. Propelling force displayed the greatest peak force in skip₂. Between the two skip steps, skip₁ had 76% lower peak propelling force over skip₂ ($p < 0.001$). Running had a maximum propelling force 54% greater than skip₁ and 49% less than skip₂, values were significant ($p < 0.001$). The impulse of the braking and propelling forces are symmetrical in the running gait, values fell between the two skip steps [table two]. The impulses in the two skip steps differed ($p < 0.001$) skip₁ had a braking force bias and skip₂ propelling. The distribution depicted in Figure 1 showed a similar positive and negative distribution in run and either a positive or negative tendency for the two skip steps [Figure 1].

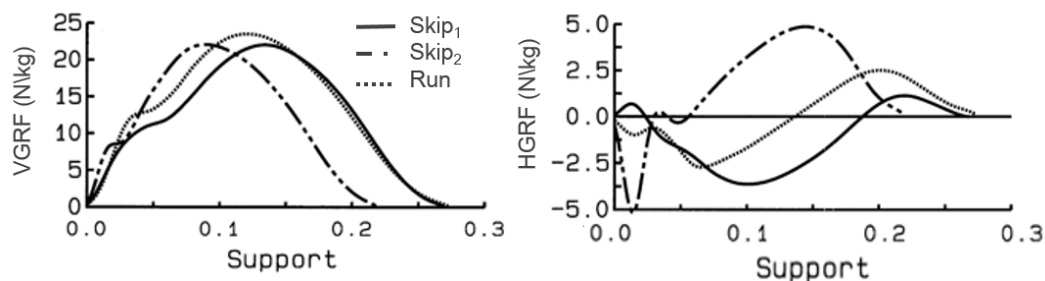


Figure 1: mean vertical (VGRF) and horizontal ground reaction forces (HGRF) measured in N/kg

Maximal extensor torque values are reported at each joint [Table 2]. The maximum hip extensor torque was greatest in skip₁ and least in skip₂, with a 77% reduction between the two steps. Run was 47% less than skip₁ and 57% more than skip₂ ($p < 0.001$). Running was 13% higher in maximum knee extensor torque imparted during skip₁ and 53% more than skip₂ ($p < 0.001$). Skip₁ was 45% higher in knee torque compared to skip₂ ($p < 0.001$). At the ankle, skip₂ experienced a 27% higher maximum extensor torque value compared to skip₁ and 15% than run ($p < 0.001$). Torque values correspond with the power generated across the stance portion of gait, with initial negative power in all three step patterns signifying the energy

dissipation and storage that occurred at hip, knee, and ankle as they flexed immediately post ground contact. Hip power was low and highly variable across all conditions (Figure 2, Table 2) and will not be discussed. Peak power differences at the knee were significant ($p < 0.001$) run had a 45% higher peak power in early stance compared to skip₁, and was 57% more than skip₂. The two skipping steps were also significantly different ($p = 0.047$) with a 22% higher peak power value in skip₁. Power at the ankle followed the same trend as ankle torque values: skip₂ was significantly higher compared with skip₁ or run ($p < 0.001$). Skip₁ was 64% lower than skip₂ and 39% slower than run. Run had a 41% lower peak negative power from skip₂. The propulsive portion of gait was typified by positive power values. Comparing maximum positive power at the knee, run was significantly greater than skip₂ by 71% ($p < 0.001$) with no significant difference from skip₁ ($p = 0.240$). There was a 69% lower peak positive power between skip₁ and skip₂ ($p < 0.001$). The skip₁ peak positive power at the ankle was 18% less than skip₂ ($p < 0.001$) and 14% less than run ($p = 0.001$). Run and skip₂ were not significantly different ($p = 0.147$).

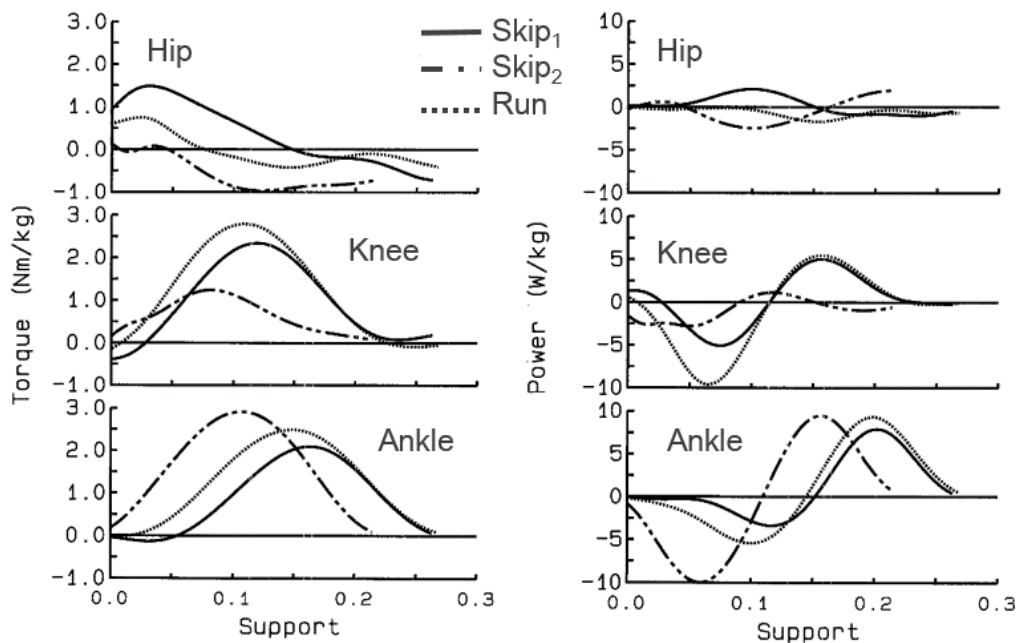


Figure 2: mean torque and power curves for the hip, knee, and ankle measured in Nm/kg

The power curves correspond directly with the work done throughout a stride, with work represented as the area under the power curve. Work is organized by negative work performed in early stance, and positive work later. Work done at the knee in the early stance phase of skipping was not significantly different between the two skipping steps ($p < 0.153$). Run, however, varied significantly between both the skipping steps absorbing 53% more energy than skip₁ and 62% more than skip₂ ($p < 0.001$). Ankle work in the early stance was greatest in skip₂, 42% more than run and 69% more than skip₁ ($p < 0.001$). The positive work done later in stance denoted the energy return. Run had a 79% increase in positive work compared with skip₂ ($p < 0.001$) with a negligible difference between skip₁ and running ($p = 0.157$). There was a significant difference between the two skipping steps, a 77% higher knee work in skip₁ ($p < 0.001$). At the ankle, skip₁ accomplished 16% less work than either skip₂ or run ($p = 0.001$, $p < 0.001$). Skip₂ and run did not differ ($p = 0.147$).

Knee Joint Loads

Knee joint loads were significantly higher in run [Figure 3] compared against either of the skip steps. The peak tibiofemoral compressive force experienced in run was 9% greater than skip₁ ($p = 0.004$) and 30% greater than skip₂ ($p < 0.001$). skip₁ produced 24% more force than skip₂ ($p < 0.001$). Peak patellofemoral compressive force was significantly higher in run compared to either of the two skip steps. Run resulted in the greatest peak patellofemoral compressive force, 16% more than skip₁ ($p = 0.002$) and 63% more than skip₂ ($p = 0.002$). Skip₂ elicited 56% less peak patellofemoral compressive force than skip₁ ($p < 0.001$).

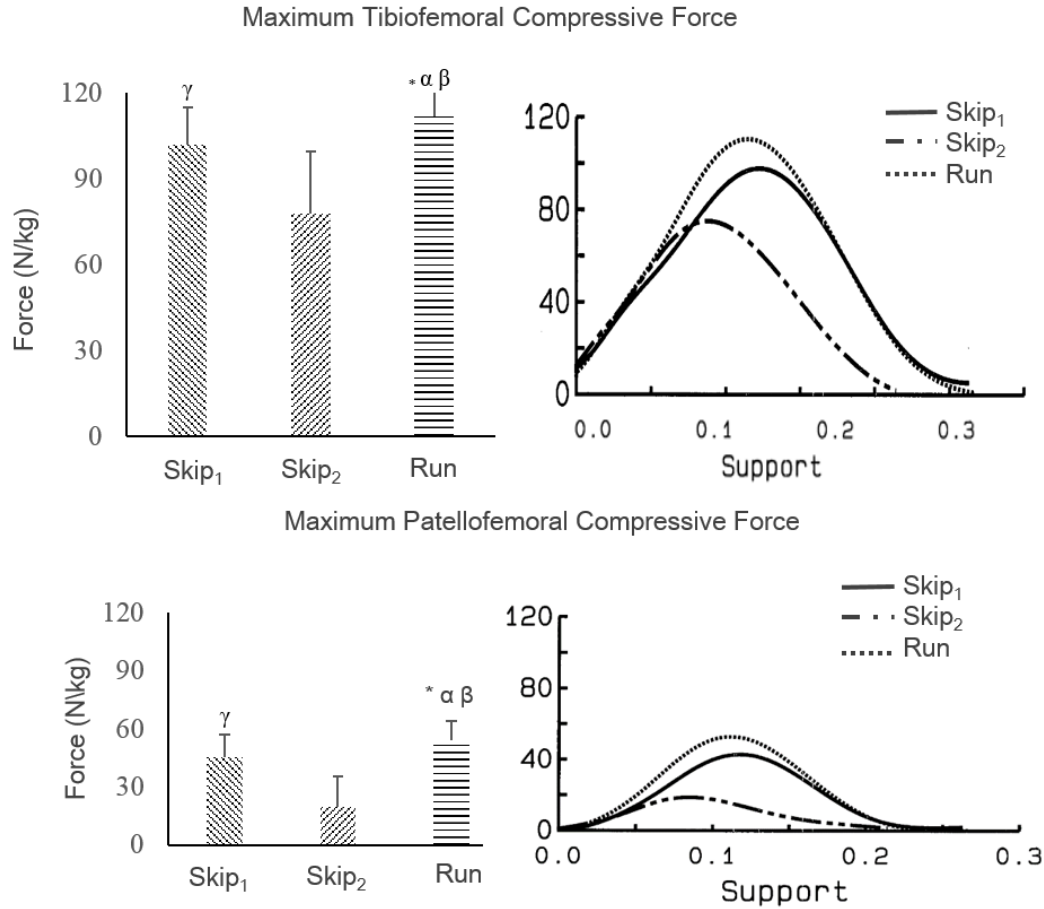


Figure 3: peak tibiofemoral compressive forces (top) peak patellofemoral compressive force (bottom) * denotes a significant omnibus F test, α indicates significant difference between skip₁ and run, β indicates significant between skip₂ and run, γ indicates significance between skip₁ and skip₂, all tests significant at $p < 0.05$

The two different steps needed to complete a skipping stride exemplifies the primary difference from running, being composed of one cyclical step repeated. When considering the movement pattern on a per distance basis, the cumulative forces and subsequent impulses may be more relatable [Table 3]. In order to skip a kilometer, it was necessary to take 20% more steps than if you were to run the same distance. The increased time on the ground resulted in a significantly greater resultant ground reaction force impulse. The tibiofemoral compressive forces were not significantly different between skipping and running, however, the patellofemoral compressive force was 38% lower in skipping.

Table 3: cumulative variables for run and skip over kilometer distance ground reaction force (GRF)

	Run	Skip
Strides (per km)*	455 (± 32)	570 (± 64)
Tibiofemoral Compressive Force (N/kg/km)	6988 (± 842)	6756 (± 779)
Patellofemoral Compressive Force (N/kg/km)*	2778 (± 715)	2015 (± 608)

* denotes significant difference at $p < 0.05$

Metabolic

As a gross measure of the cost of each movement pattern, the rate of oxygen consumption was compared between skipping running. Standing cost was used a baseline value and displayed for visual comparative ease. Skipping consumed an average 27% more oxygen than running and resulted in 36% more calories burned per unit time. Values are consistent with the literature, ACSM calculated the cost of running at 2.68 m/s to be 14.9 kcal/min, our mean running value equaled 14.86 kcal/min.⁶²

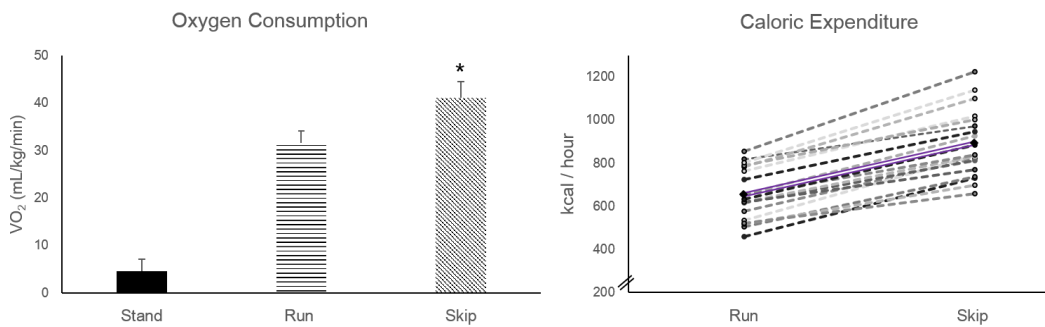


Figure 4: metabolic cost measured in ml/kg/min with sd displayed with error bars (left) Caloric expenditure measured in kcal/hour average value displayed with solid purple line(right) *denotes significant difference between values

Summary

Not only are skipping and running significantly different from one another in both kinetics, kinematics, and metabolic, the two skipping steps differed significantly. In general, running implicated a greater peak vertical ground reaction force, maximal knee extensor torque,

peak negative power and work in early stance and peak maximal positive power at the knee, as well as higher peak tibiofemoral and patellofemoral compressive force, as compared to skipping. Conversely, skipping was accomplished with an increase in cadence, maximal horizontal ground reaction force, maximum hip and ankle extensor torque, peak negative power and work, positive power at the ankle, and a greater energy demand. Among the two skipping steps, skip₂ had the highest cadence, horizontal ground reaction force peak, maximum ankle extensor torque, peak negative power, work, and positive power.

Chapter V Discussion

The study was designed to investigate skipping as an alternate movement pattern in comparison to running. The first purpose was to compare basic gait characteristics; lower extremity kinematics and kinetics including ground reaction forces, joint torques, and powers in skipping and running. The second purpose was to investigate the knee loads in skipping by comparing tibiofemoral and patellofemoral joint forces in skipping and running. The final purpose was to compare the metabolic cost of skipping to that of running. Skipping has previously been underrepresented in the literature; together the variables of interest attempted to comprehensively describe the movement of skipping in comparison to running. The two skipping steps were periodically averaged in order to represent the forces transmitted across the cumulative contact phases of a stride.

Purpose One

Skipping is unique in that there are two alternating steps that complete a stride, as opposed to running which is composed of one cyclical motion. The initial step forward is referred to as skip₁ with skip₂ being the subsequent hop on the same foot: right right– left left, repeated. The two skipping steps are significantly different in many kinematic components [Table 2]. Skip₁ had the longest stride length of the three steps whereas skip₂ had the shortest. Typically a shorter stride length is accomplished with a decreased hip range of motion.¹⁴ This holds true when evaluating each skip stride as an independent variable skip₁ presented with the largest excursion and largest stride while skip₂ showed the smallest range and stride length [Table 2]. Decreases in stride length are coordinated with increases in stride rate when movement speed is constant.³³ This inverse relationship between stride length and rate is supported in our data, with per step cadence being greatest in the shortest strode (skip₂) and smallest in our longest stride (skip₁). Minetti et al. has also reported an increased stride

frequency in skipping compared to running.¹³ Increases in cadence have been shown in the literature to have significant effects on total and regional plantar loading in running. Despite the varying kinematic approaches to skipping and running, the inverse relationship of increased and total foot plantar loading variables will likely hold true; with contact time, total foot peak force, and total foot peak pressure decreasing with the increased cadence seen in skipping.⁶³

Ground reaction force values are highly dependent on the velocity of the movement, with an increased ground reaction force typically eliciting increased speed.^{64,65} Johnson et al. reported a 20% decrease in peak vertical ground reaction forces between skipping and running. That particular study had participant's self-select speeds with running unanimously occurring at increased velocity (skip: 1.75 m/s run: 3.83 m/s).¹¹ The present study controlled speed by having participants perform both movements at 2.68 m/s in order to effectively demonstrate the differences in force values due to movement differences. Skipping was accomplished with an average stride length of 1.81 m compared to the 2.21 m length for running. A decreased stride length of this degree has been previously shown to decrease subsequent ground reaction forces.^{33,66} This finding was supported with a decreased maximal peak vertical ground reaction force accompanying the smaller stride length associated with skipping. Alternately, skipping had a significant increase in horizontal ground reaction forces. Johnson et al. found no change in the skipping and running horizontal ground reaction forces, but as stated above, the two movement speeds were not constant.¹¹ The cumulative resultant ground reaction force impulse reflected the total load the body was subjected to over the course of a kilometer.⁶⁷ The skipping pattern resulted in a significant net increase resultant ground reaction force impulse [Table 2].

The data presented in this skipping study show that the two skipping steps vary in the magnitude of force. Skip₂ displayed much greater values for both braking and propulsion

components. Skip₁ displayed greater peak braking force compared to run but not as much propulsive force. The impulse of the horizontal ground reaction forces [Table 2, Figure 1] clearly demonstrated the difference in the two skipping steps. To first look at run, the horizontal ground reaction force curve illustrated a generally equal distribution between braking and propelling with initial negative values followed by a positive period. This cyclical negative and positive energy distribution was accomplished each step. Skipping alternately showed a step by step dichotomy. One step functioned in a predominant absorption or propulsion manor.⁶⁸ Skip₁ had a braking force impulse four times that of skip₂ implying that it was an eccentric dominant step. Conversely, skip₂ was a concentric dominant step as shown by the net positive horizontal ground reaction force impulse. Together the two skip steps accomplished the cyclical negative and positive energy exchange necessary to achieve forward motion with the balance occurring after a stride as opposed to each step typified in running.

Ground reaction forces represent the net muscle, gravitational, and inertial forces acting throughout contact phase. The direction and magnitude of the forces, both internal and external, in conjunction with the length of the moment arm contribute to the torque experienced at each joint. A measured decrease in vertical ground reaction force and peak power and work done at the knee in skipping contributed to the decreased extensor torque at the knee. The hip and ankle experienced greater peaks in extensor torques when comparing skip to run. This was in part explained by the larger hip range of motion across a stride. An increased range of motion typically implies a larger moment arm and thus torque.^{69,70} The greater negative peak power and work at the ankle implied an increase in internal forces^{71,72} [Table 2 and 4] and can substantiate the increased torque measured at the ankle.

Table 4: mean knee and ankle range of motion through stance phase of gait

Variable of Interest	Run	Skip ₁	Skip ₂
Hip Range of Motion (deg)	26.3°	39.9°	20.7°
Ankle Range of Motion (deg)	39.2°	32.3°	35.9°

The increased net-work established in skipping was associated with the increased braking and propelling impulse values. The segregation of braking and propulsive impulses between the steps indicated that each skipping step had a specific function, this is a key difference between the two gait patterns. Each running step was temporally and spatially symmetrical. The result was a nearly perfect balance of energy, as seen in total support work value of -0.08 J/kg [Table 2]. Alternately, each skipping step performed distinctly different functions. The first footfall (skip₁) was responsible for slowing the body down as demonstrated by the significantly greater braking impulse. The second footfall, alternately, was responsible for propelling the body forward into the next step [Table 2]. Overall, the support work throughout the contact phase was greater in skipping despite the fact that running exhibited great peak values at the knee in early and late stages of contact and at the ankle in the late stage.

Purpose one examined the kinematic and kinetic changes revealed an increased stride length, decreased vertical ground reaction force, increased horizontal ground reaction force, decreased knee torque, increased hip and ankle torque, decreased knee power and work throughout, and increased ankle power and work in the initial phase of contact with less positive work in the later portion of contact.

Purpose Two

Lower extremity injuries are often attributed to the lower extremity joints being unable to adequately control the loads applied throughout contact with the ground.^{33,73} High loads are specifically cited as an indicator for injury.^{57,74,75} Skipping displayed significantly lower peak

compressive forces than running at both tibiofemoral and patellofemoral surfaces. Skip₁ had a 9% decrease while skip₂ had a 30% decrease compared to run at the tibiofemoral joint. At the patellofemoral joint skip₁ had a 16% decrease while skip₂ had a 56% decrease, when compared to run. While self-selected running and skipping speeds may vary, participants performed at a constant 2.68 m/s throughout collection. The reduced knee loads were not on account of a slower speed.

The two steps composition of skipping necessitates an increased number of steps taken to traverse a unit distance. The per step force data confirmed a significant decrease in peak knee loads in skipping compared to running. The impulse considered the time integer of these forces. It stands that with an increased number of steps taken over a kilometer, an increased occurrence of force application would be applied to the body, potentially mollifying the benefits seen in the per step data.⁷⁶ Yet, despite the 20% increased number of steps taken over a unit distance, cumulative patellofemoral compressive force were significantly less in skip compared to run. There was no significant difference between the two gait pattern's cumulative tibiofemoral compressive forces. Skipping remains a beneficial alternative to running over the course of a kilometer, in spite of the increased number of steps.

The knee forces reported in our study are consistent with the literature when considering the speed of movement. Willson et al. had participants run at 2.84 m/s and reported similar average patellofemoral peak forces of 57.86 N/kg. Participants in this study ran at 2.68 m/s and peak patellofemoral force was calculated to be 54 N/kg.^{77,78} The 7% discrepancy can be attributed to speed discrepancies. There have not been any previous studies reporting knee forces in skipping.

Decreased knee compressive forces are correlated with a decreased stride length [Figure 5-6] which, in turn is inversely correlated with stride rate. This pattern is seen throughout the literature, with stride length and rate being directly related with decreased stride length resulting in an increase in step rate.^{33,79} Heiderscheit et al. reported a 10% increase in stride rate reduced energy absorption at the hip and knees while a 5% increase reduced total knee work.^{33,77} Hamill and Derrick have separately shown that stride length affects the level of shock imparted on the lower extremity with decreased stride length (or increased step rate) associated with decreased force impact peaks.^{79,80} Lenhart et al. and Chumanova et al. both concluded a decreased in stride length manipulated muscle patterns and induced a decrease in extensor muscle force and peak patellar tendon force throughout stance.^{66,81}

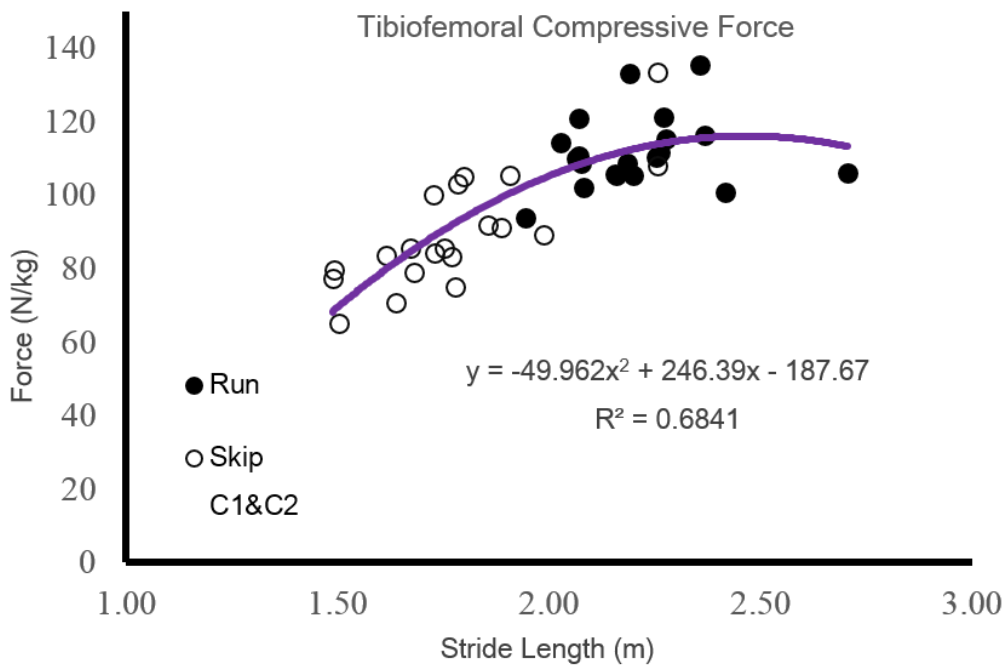


Figure 5: Correlation between stride length and Tibiofemoral compressive force

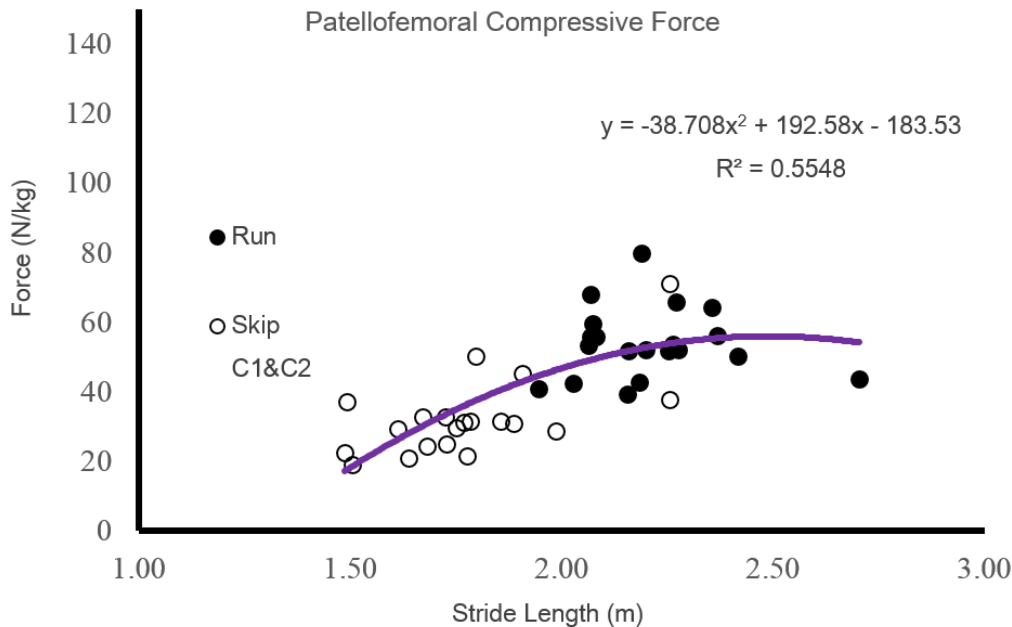


Figure 6: Correlation between stride length and patellofemoral compressive force

The curvilinear relationship displayed between knee forces and stride lengths illustrated the benefits of a decreased stride length, and represented the potential boundaries. The stride length and compressive force relationship was not mutually exclusive as seen in the R^2 values of 0.68 for tibiofemoral [Figure 5] and 0.55 for patellofemoral [Figure 6]. The curvilinear fit indicated that there are likely upper and lower bounds to adjusting stride length and decreasing knee forces.¹⁴ Further, a smaller stride length does not always result in decreased knee compressive forces.³³ Individual data points exemplified that there is some variability and intra-subject inconsistency in movement patterns. Some subjects chose to skip with a longer stride lengths which resulted in increased knee force values and visa-versa.^{28,82,83} The data displayed in figure 5 and 6 are taken from all participants trial averages and mass normalized knee forces on a per step basis.

Purpose two established a decreased knee compressive forces in skipping compared to running on a per step and per km basis. This decreased compressive force is relevant as some

reports approximate nearly half of all running related injuries occur at the knee with an estimated half of those involving the patellofemoral joint.^{33,84} The knee force values were proposed to be directly correlated with stride length, with decreased stride length resulting in decreased knee compressive forces.

Purpose Three

Measures of oxygen consumption are gross appraisals of energy used to complete an activity while energy expresses the cost of movement in terms of caloric cost.⁸⁵ Muscles transform metabolic energy in force, how a muscle is specifically function determines the cost of an action. The combination of internal and external forces: movement of limbs relative to the whole body center of mass, and movement of the whole body's center of mass relative to the ground, describe muscle function.⁴⁷ Individual aspects of movement contribute to the gross cost of transport in varying ratios with the most prominent consideration being the levels of contraction necessary to support body weight, perform work to redirect and accelerate the center of mass, and maintain stability.^{15,35,47} Kram et al. has shown that the cost of performing work is nearly twice the cost of generating force.¹⁵ The cost of generating force throughout contact is dependent on the magnitude and rate of muscle force generation.³⁵

The increase in oxygen consumption (mL/kg/min) and in caloric cost (kcal/hour) between skip and run may be explained by the differences in work done on the center of mass with the assumption that skipping and running require the same levels of contraction necessary to support body weight and maintain stability. Justifying the assumption of equal levels of contraction necessary to maintain stability, consider the double support phase seen in skipping but not running. Minetti commented on the increased stability provided by this double support phase of skipping¹² and Johnson et al. concluded that the double support phase made the gait a valuable tool in the rehabilitation setting in progressing and injury from walking to running.¹¹

Calculated cost of performing work on a body's center of mass; redirecting and accelerating, comprises 45% of the net metabolic cost.^{14,15} It follows that if a movement pattern has a larger vertical displacement there will be a greater demand for oxygen. The change in vertical position was nearly double in skip versus run, indicative of a correlation between metabolic cost and vertical displacement [Figure 7]. Gordon et al. attempted to control for vertical displacement to assess the relationship between center of mass displacement and metabolic cost. They found that reduced center of mass displacement is not metabolically advantageous. However, the study participants all adopted a 'groucho' style gait resulting in increased work.¹⁴ The vertical displacement measured in our study was all self-selected, meaning we did not control for how each individual chose to successfully complete each locomotion pattern. Despite that, *all* skipping gaits resulted in a greater vertical excursion, without a single exception. Figure 7 shows a clear segregation between the two gaits measured vertical displacement. Additionally, the training program completed prior to collection entailed skipping a cumulative minimum of three miles ensuring the movement pattern was not novel and each participant had enough experience to adopt a comfortable technique.^{52,86} The correlation between metabolic cost and vertical displacement [figure seven] had a R^2 value of 0.64 indicative of a strong relationship. While some individual data points did not epitomize the correlation, the data set distribution confirmed a distinct segregation between the two movement patterns with a greater vertical displacement when skipping thus, greater metabolic cost. The magnitude of change between the two gaits was also found by Minetti et al. who reported

skipping to be up to 30% more metabolically costly than running.¹³

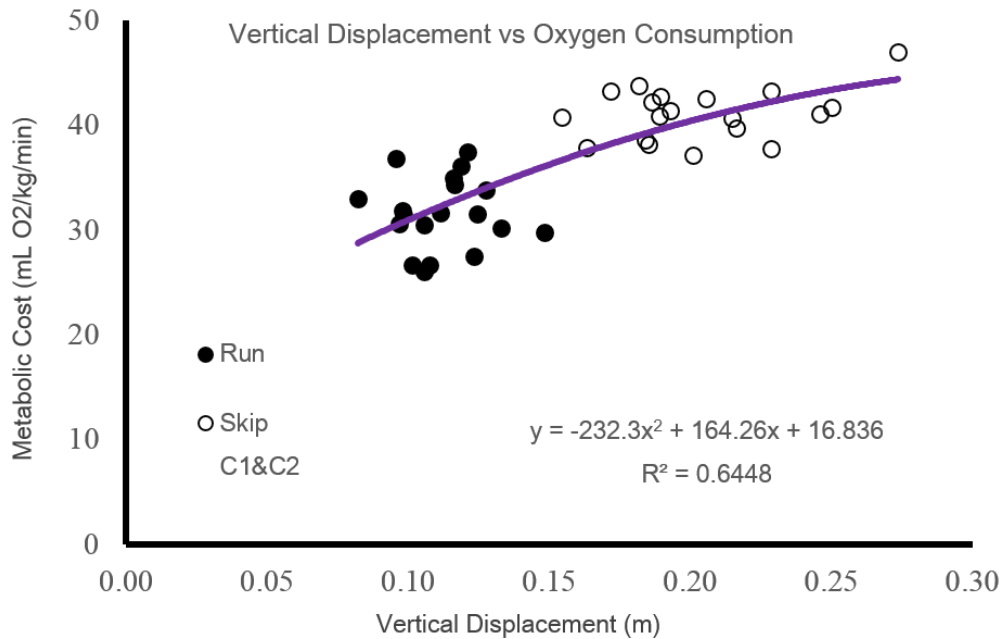


Figure 7: Correlation between vertical displacement and metabolic cost

Skipping and running can both be classified as bouncing gaits, signifying that throughout the propulsive portion of the contact phase tendons are known to stretch and recoil; releasing stored elastic strain energy.^{48,55,68} This cyclical pattern of storing and releasing energy has been proposed as a mechanism for reducing the total amount of metabolic energy expended during locomotion.⁵⁰ Skipping had a striking increase in metabolic cost paired with a general decrease in work, which is counter intuitive as metabolic cost is a gross estimation of muscle function. Perhaps the benefits of stored energy are diminished across the separate steps in skipping.

The cost of transport is an optimization of many factors and a function of the cumulative metabolic rates of the muscles that produce locomotion and maintain stability.⁵¹ As muscle systems develop habitual optimal economy and neurological control of the desired motion, there is a reduced cost of activity and therefore a decreased imposed demand upon the body, and diminished training effects.⁵² Measures of metabolic cost represent energy usage and can be

used as a benchmark evaluation of cardiovascular and musculoskeletal benefits obtainable with a particular activity.^{18,85} Skipping will utilize 36% more calories compared to running at the same speed and gradient which works out to be an additional 236 kcal/hour. For the same unit time or distance skipping provides significantly greater aerobic benefits compared to running.¹⁸

Conclusion

When comparing skipping and running, skipping presents reduced maximum ground reaction forces, reduced knee torque, reduced knee compressive forces, and an increased caloric expenditure. With many of these factors accused of predisposing individuals to running related injuries, skipping presents an attractive alternative with an increased return of benefits associated with aerobic exercise. While acknowledging that running presents performance outcome advantages over skipping in several settings, incorporating skipping into a training regimen may be beneficial to those suffering from or at risk of running related injuries.⁵

Increasing oxygen consumption by 27% and caloric consumption by 36% allows an individual to work out for less time or distance while maintaining the same benefits and in this case, decrease risks of knee injury. Alternately, more benefits can be incurred while maintaining time or distance previously used for running, while decreasing risk of knee injury.

References

1. Running USA. 2014 state of the sport - part II: Running industry report. 2014;2.
2. Goss DL, Gross MT. *A review of mechanics and injury trends among various running styles*. 2012.
3. Jin J. Running injuries. *JAMA*. 2014;312(2):202.
4. Scott SH, Winter DA. Internal forces of chronic running injury sites. *Med Sci Sports Exerc*. 1990;22(3):357.
5. Malisoux L, Nielsen RO, Urhausen A, Theisen D. A step towards understanding the mechanisms of running-related injuries. *Journal of Science and Medicine in Sport*. 2015;18(5):523-528.
6. Blair SN, Kohl HW, Goodyear NN. Rates and risks for running and exercise injuries: Studies in three populations. *Res Q Exerc Sport*. 1987;58(3):221-228.
7. Winter DA. Overall principle of lower limb support during stance phase of gait. *J Biomech*. 1980;13(11):923-927.
8. Kerrigan DC, Franz JR, Keenan GS, Dicharry J, Della Croce U, Wilder RP. The effect of running shoes on lower extremity joint torques. *PM&R*. 2009;1(12):1058-1063.
9. Barr AE, Barbe MF. Pathophysiological tissue changes associated with repetitive movement: A review of the evidence. *Phys Ther*. 2002;82(2):173-187.
10. Robertson MA. Testing the validity of the halverson developmental sequences for skipping. *Res Q Exerc Sport*. 2013;84(2):198-205.
11. Johnson ST, Golden GM, Mercer JA, Mangus BC, Hoffman MA. Ground-reaction forces during form skipping and running. *J Sport Rehab*. 2005;14(4):338-345.
12. Minetti AE. The biomechanics of skipping gaits: A third locomotion paradigm? *Proceedings: Biological Sciences*. 1998;265(1402):1227-1235.
13. Minetti AE, Pavei G, Biancardi CM. The energetics and mechanics of level and gradient skipping: Preliminary results for a potential gait of choice in low gravity environments. *Planet Space Sci*. 2012;74(1):142-145.
14. Gordon KE, Ferris DP, Kuo AD. Metabolic and mechanical energy costs of reducing vertical center of mass movement during gait. *Arch Phys Med Rehabil*. 2009;90(1):136-144.
15. Grabowski A, Farley CT, Kram R. Independent metabolic costs of supporting body weight and accelerating body mass during walking. *J Appl Physiol (1985)*. 2005;98(2):579-583.
16. Srinivasan M, Ruina A. Idealized walking and running gaits minimize work. *Proceedings: Mathematical, Physical and Engineering Sciences*. 2007;463(2086):2429-2446.
17. Ackermann M, van den Bogert AJ. Predictive simulation of gait at low gravity reveals skipping as the preferred locomotion strategy. *J Biomech*. 2012;45(7):1293-8.
18. Warburton DE, Nicol CW, Bredin SS. Prescribing exercise as preventive therapy. *CMAJ*. 2006;174(7):961-974.
19. Buist I, Bredeweg SW, Lemmink KA, van Mechelen W, Diercks RL. Predictors of running-related injuries in novice runners enrolled in a systematic training program: A prospective cohort study. *Am J Sports Med*. 2010;38(2):273-280.
20. van Mechelen W. Running injuries. *Sports Medicine*. 1992;14(5):320-335.
21. Zatsiorsky VM. *Kinematics of human motion*. Human Kinetics; 1998.
22. Robertson G, Caldwell G, Hamill J, Kamen G, Whittlesey S. *Research methods in biomechanics, 2E*. Human Kinetics; 2013.
23. A. Belli, H. Kyröläinen, P. V. Komi. Moment and power of lower limb joints in running. *Int J Sports Med*. 2002;23(2):136-141.
24. Thordarson DB. Running biomechanics. *Clin Sports Med*. 1997;16(2):239-247.

25. Kirtley C. *Clinical gait analysis: Theory and practice*. New York: Elsevier; 2006.
26. Pandy MG, Andriacchi TP. Muscle and joint function in human locomotion. *Annu Rev Biomed Eng*. 2010;12:401-433.
27. *Developmental physical education for all children + journal access*. Human Kinetics; 2007.
28. Winter DA. Kinematic and kinetic patterns in human gait: Variability and compensating effects. *Human Movement Science*. 1984;3(1-2):51-76.
29. Keller TS, Weisberger AM, Ray JL, Hasan SS, Shiavi RG, Spengler DM. Relationship between vertical ground reaction force and speed during walking, slow jogging, and running. *Clin Biomech*. 1996;11(5):253-259.
30. Munro CF, Miller DI, Fuglevand AJ. Ground reaction forces in running: A reexamination. *J Biomech*. 1987;20(2):147-155.
31. McFadyen BJ, Winter DA. An integrated biomechanical analysis of normal stair ascent and descent. *J Biomech*. 1988;21(9):733-744.
32. Winter DA. Biomechanical motor patterns in normal walking. *J Mot Behav*. 1983;15(4):302-330.
33. Heiderscheit BC, Chumanov ES, Michalski MP, Wille CM, Ryan MB. Effects of step rate manipulation on joint mechanics during running. *Med Sci Sports Exerc*. 2011;43(2):296-302.
34. Winter DA. Moments of force and mechanical power in jogging. *J Biomech*. 1983;16(1):91-97.
35. Griffin TM, Roberts TJ, Kram R. Metabolic cost of generating muscular force in human walking: Insights from load-carrying and speed experiments. *J Appl Physiol (1985)*. 2003;95(1):172-183.
36. Miller RH, Brandon SC, Deluzio KJ. Predicting sagittal plane biomechanics that minimize the axial knee joint contact force during walking. *J Biomech Eng*. 2013;135(1):011007.
37. McGowan CP, Baudinette RV, Biewener AA. Joint work and power associated with acceleration and deceleration in tammar wallabies (*macropus eugenii*). *J Exp Biol*. 2005;208(Pt 1):41-53.
38. Crowninshield RD, Brand RA. A physiologically based criterion of muscle force prediction in locomotion. *J Biomech*. 1981;14(11):793-801.
39. Lin Y, Dorn TW, Schache AG, Pandy MG. Comparison of different methods for estimating muscle forces in human movement. *Proc Inst Mech Eng Part H J Eng Med*. 2011;0954411911429401.
40. Erdemir A, McLean S, Herzog W, van den Bogert, Antonie J. Model-based estimation of muscle forces exerted during movements. *Clin Biomech*. 2007;22(2):131-154.
41. Riemer R, Hsiao-Wecksler ET, Zhang X. Uncertainties in inverse dynamics solutions: A comprehensive analysis and an application to gait. *Gait Posture*. 2008;27(4):578-588.
42. Tsai T, Lu T, Kuo M, Lin C. Effects of soft tissue artifacts on the calculated kinematics and kinetics of the knee during stair-ascent. *J Biomech*. 2011;44(6):1182-1188.
43. Messier SP, Legault C, Loeser RF, et al. Does high weight loss in older adults with knee osteoarthritis affect bone-on-bone joint loads and muscle forces during walking? *Osteoarthritis and Cartilage*. 2011;19(3):272-280.
44. Rugg S, Gregor R, Mandelbaum B, Chiu L. In vivo moment arm calculations at the ankle using magnetic resonance imaging (MRI). *J Biomech*. 1990;23(5):495-501.
45. Spoor C, Van Leeuwen J. Knee muscle moment arms from MRI and from tendon travel. *J Biomech*. 1992;25(2):201-206.
46. Schipplein O, Andriacchi T. Interaction between active and passive knee stabilizers during level walking. *Journal of Orthopaedic Research*. 1991;9(1):113-119.
47. Arellano CJ, Kram R. The energetic cost of maintaining lateral balance during human running. *J Appl Physiol (1985)*. 2012;112(3):427-434.

48. Nigg BM, Herzog W. *Biomechanics of the musculo-skeletal system*. Wiley; 2007.
49. Brockway JM. Derivation of formulae used to calculate energy expenditure in man. *Human nutrition. Clinical nutrition*. 1987;41(6):463.
50. Alexander R. The spring in your step: The role of elastic mechanisms in human running. *Biomechanics XI-A. (Edited by G.de Groot, AP Hollander, PA Huijting, and GI van Ingen Schenau)*. 1988:17-25.
51. Carrier DR, Anders C, Schilling N. The musculoskeletal system of humans is not tuned to maximize the economy of locomotion. *Proc Natl Acad Sci U S A*. 2011;108(46):18631-18636.
52. Perez MA, Lungholt BK, Nyborg K, Nielsen JB. Motor skill training induces changes in the excitability of the leg cortical area in healthy humans. *Experimental Brain Research*. 2004;159(2):197-205.
53. Heise GD, Smith JD, Martin PE. Lower extremity mechanical work during stance phase of running partially explains interindividual variability of metabolic power. *Eur J Appl Physiol*. 2011;111(8):1777-1785.
54. van Ingen Schenau GJ. Some fundamental aspects of the biomechanics of overground versus treadmill locomotion. *Med Sci Sports Exerc*. 1980;12(4):257-261.
55. Saibene F, Minetti AE. Biomechanical and physiological aspects of legged locomotion in humans. *Eur J Appl Physiol*. 2003;88(4):297-316.
56. Soutas-Little RW. SECTION TWO. *Gait Analysis In The Science Of Rehabilitation*. 1998;2:49.
57. Nigg B, Bahlisen H, Luethi S, Stokes S. The influence of running velocity and midsole hardness on external impact forces in heel-toe running. *J Biomech*. 1987;20(10):951-959.
58. Matsas A, Taylor N, McBurney H. Knee joint kinematics from familiarised treadmill walking can be generalised to overground walking in young unimpaired subjects. *Gait Posture*. 2000;11(1):46-53.
59. Kaneko M. Mechanics and energetics in running with special reference to efficiency. *J Biomech*. 1990;23:57-63.
60. Messier SP, Legault C, Schoenlank CR, Newman JJ, Martin DF, DeVita P. Risk factors and mechanisms of knee injury in runners. *Med Sci Sports Exerc*. 2008;40(11):1873-1879.
61. DeVita P, Hortobagyi T. Age causes a redistribution of joint torques and powers during gait. *J Appl Physiol (1985)*. 2000;88(5):1804-1811.
62. American College of Sports Medicine. *ACSM's guidelines for exercise testing and prescription*. Lippincott Williams & Wilkins; 2013.
63. Wellenkotter J, Kernozek TW, Meardon S, Suchomel T. The effects of running cadence manipulation on plantar loading in healthy runners. *Int J Sports Med*. 2014;35(9):779-784.
64. Cavanagh PR, LaFortune MA. Ground reaction forces in distance running. *J Biomech*. 1980;13(5):397-406.
65. Hamill J, Bates B, Knutzen K, Sawhill J. Variations in ground reaction force parameters at different running speeds. *Human Movement Science*. 1983;2(1):47-56.
66. Lenhart RL, Thelen DG, Wille CM, Chumanov ES, Heiderscheid BC. Increasing running step rate reduces patellofemoral joint forces. *Med Sci Sports Exerc*. 2014;46(3):557-564.
67. Hunter JP, Marshall RN, McNair PJ. Relationships between ground reaction force impulse and kinematics of sprint-running acceleration. *J Appl Biomech*. 2005;21(1):31-43.
68. Fiers P, De Clercq D, Segers V, Aerts P. Biomechanics of human bipedal gallop: Asymmetry dictates leg function. *J Exp Biol*. 2013;216(Pt 7):1338-1349.
69. Delp SL, Hess WE, Hungerford DS, Jones LC. Variation of rotation moment arms with hip flexion. *J Biomech*. 1999;32(5):493-501.
70. Visser J, Hoogkamer J, Bobbert M, Huijting P. Length and moment arm of human leg muscles as a function of knee and hip-joint

- angles. *Eur J Appl Physiol Occup Physiol*. 1990;61(5-6):453-460.
71. Glitsch U, Baumann W. The three-dimensional determination of internal loads in the lower extremity. *J Biomech*. 1997;30(11):1123-1131.
72. Zhao D, Banks SA, Mitchell KH, D'Lima DD, Colwell CW, Fregly BJ. Correlation between the knee adduction torque and medial contact force for a variety of gait patterns. *Journal of Orthopaedic Research*. 2007;25(6):789-797.
73. O'Leary K, Vorpahl KA, Heiderscheid B. Effect of cushioned insoles on impact forces during running. *J Am Podiatr Med Assoc*. 2008;98(1):36-41.
74. Radin EL, Parker HG, Pugh JW, Steinberg RS, Paul IL, Rose RM. Response of joints to impact loading—III: Relationship between trabecular microfractures and cartilage degeneration. *J Biomech*. 1973;6(1):51IN955-54IN1157.
75. James CR, Bates BT, Dufek JS. Classification and comparison of biomechanical response strategies for accommodating landing impact. *Journal of Applied Biomechanics*. 2003;19(2):106-118.
76. Miller RH, Edwards WB, Brandon SC, Morton AM, Deluzio KJ. Why don't most runners get knee osteoarthritis? A case for per-unit-distance loads. *Med Sci Sports Exerc*. 2014;46(3):572-579.
77. Willson JD, Sharpee R, Meardon SA, Kernozek TW. Effects of step length on patellofemoral joint stress in female runners with and without patellofemoral pain. *Clin Biomech*. 2014;29(3):243-247.
78. Willson JD, Loss JR, Willy RW, Meardon SA. Sex differences in running mechanics and patellofemoral joint kinetics following an exhaustive run. *J Biomech*. 2015;48(15):4155-4159.
79. Hamill J, Derrick T, Holt K. Shock attenuation and stride frequency during running. *Human Movement Science*. 1995;14(1):45-60.
80. Derrick TR, Hamill J, Caldwell GE. Energy absorption of impacts during running at various stride lengths. *Med Sci Sports Exerc*. 1998;30(1):128-135.
81. Chumanov ES, Wille CM, Michalski MP, Heiderscheid BC. Changes in muscle activation patterns when running step rate is increased. *Gait Posture*. 2012;36(2):231-235.
82. Nigg BM, Baltich J, Hoerzer S, Enders H. Running shoes and running injuries: Mythbusting and a proposal for two new paradigms: 'Preferred movement path' and 'comfort filter'. *Br J Sports Med*. 2015.
83. Weyand PG, Davis JA. Running performance has a structural basis. *J Exp Biol*. 2005;208(Pt 14):2625-2631.
84. Taunton JE, Ryan MB, Clement DB, McKenzie DC, Lloyd-Smith DR, Zumbo BD. A retrospective case-control analysis of 2002 running injuries. *Br J Sports Med*. 2002;36(2):95-101.
85. Harrell JS, McMurray RG, Baggett CD, Pennell ML, Pearce PF, Bangdiwala SI. Energy costs of physical activities in children and adolescents. *Med Sci Sports Exerc*. 2005;37(2):329-336.
86. Schoner G, Kelso JA. Dynamic pattern generation in behavioral and neural systems. *Science*. 1988;239(4847):1513-1520.

APPENDIX A

Institutional Review Board Approval



EAST CAROLINA UNIVERSITY
University & Medical Center Institutional Review Board Office
4N-70 Brody Medical Sciences Building- Mail Stop 682
600 Moye Boulevard · Greenville, NC 27834
Office 252-744-2914 · Fax 252-744-2284 · www.ecu.edu/irb

Notification of Initial Approval: Expedited

From: Biomedical IRB
To: [Paul DeVita](#)
CC: [Patrick Rider](#)
Date: 4/7/2015
Re: [UMCIRB 15-000267](#)
Comparing the biomechanics and metabolic differences between skipping and running

I am pleased to inform you that your Expedited Application was approved. Approval of the study and any consent form(s) is for the period of 4/7/2015 to 4/6/2016. The research study is eligible for review under expedited category # 4,6. The Chairperson (or designee) deemed this study no more than minimal risk.

Changes to this approved research may not be initiated without UMCIRB review except when necessary to eliminate an apparent immediate hazard to the participant. All unanticipated problems involving risks to participants and others must be promptly reported to the UMCIRB. The investigator must submit a continuing review/closure application to the UMCIRB prior to the date of study expiration. The Investigator must adhere to all reporting requirements for this study.

Approved consent documents with the IRB approval date stamped on the document should be used to consent participants (consent documents with the IRB approval date stamp are found under the Documents tab in the study workspace).

The approval includes the following items:

Name	Description
General Protocol-short description	Study Protocol or Grant Application
Phone Interview- Initial health survey	Recruitment Documents/Scripts
Recruitment Flyer	Recruitment Documents/Scripts
Revised Informed Consent Form	Consent Forms

The Chairperson (or designee) does not have a potential for conflict of interest on this study.

Appendix B

Initial Phone Interview

Comparison of Running and Skipping Gaits Health Survey To Determine Eligibility For Research Participants

“Hi (participant), my name is (_____) and I’m (a graduate student/an intern) in the biomechanics lab at ECU, how are you? I’m calling about your interest in being a participant in our Comparison of Running and Skipping Gaits study. Do you mind if I ask you some questions on our health survey?”

Demographic data:

Date _____

Name _____ Phone number _____

Email address

Birth date _____

Age _____

Height (ft/in) _____

Height (m) _____

Weight (lbs) _____

Mass (kg) _____

BMI (kg/m²) _____

Do you smoke?

Yes ___ No ___

Have you smoked in the past?

Yes ___ No ___

If yes, when did you stop smoking _____

On average, how often do you exercise (3 day/week is minimum)?

Days a week:

Time:

What sort of activities do you do when you exercise?(Lift weights? Play a sport? Endurance exercises?)

During the past year, did you experience pain while working out?

Yes ___ No ___ If yes, from _____

Medical:

Do you have any other musculoskeletal problems such as hip arthritis, joint replacement, or other orthopedic problems? Yes ___ No ___

Do you have any neurological problems such as stroke or Parkinson’s disease? Yes ___ No ___

Do you have any problems with your heart such as atrial fibrillation, pace maker, coronary artery disease, or congestive heart failure? Yes____ No ____

Do you have any pulmonary diseases such as difficulty in breathing or emphysema?
Yes__No____

Do you have any peripheral artery disease? Yes____ No ____

Do you have high blood pressure (>160/90 mm Hg)? Yes____ No ____

Do you take medication to control your blood pressure? Yes____ No____

List the medications you are currently taking

Do you have any other medical problems we did not talk about? Yes____ No____

If, "Yes," what is or are the conditions? _____

List any surgeries you have had.

If you have one, please tell us your physician's name, telephone number, and clinic name:

"If completed, you will be paid \$25 for your participation in our study. Our first meeting will consist of completing paperwork and going outside to begin training, it should take under 1 hour to complete. Please wear comfortable clothes (sneakers, shorts/spandex, t-shirt, normal exercise clothing). Are you available at any time this or next week to schedule a meeting time?"

