Relationship of Fatigued Run and Rapid Stop to Ground Reaction Forces, Lower Extremity Kinematics, and Muscle Activation

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Fatigue may be related to lower extremity injury. The effect of lower extremity fatigue on ground reaction force production, lower extremity kinematics, and muscle activation during the landing phase of a run and rapid stop was investigated. Subjects were 19 female, Division 1 collegiate basketball and volleyball players ($\bar{X}$ age = 20.8 ± 1.8 years, $\bar{X}$ weight = 71.7 ± 6.9 kg, $\bar{X}$ height = 174 ± 5 cm). Dominant leg ground reaction and muscle activation data were sampled at 2,000 Hz. Lower extremity kinematic data were sampled at 200 Hz, and three-dimensional analysis was performed. Knee extensor/flexor muscle activation tended to be delayed during fatigue ($p \leq .08$). Maximum knee flexion tended to occur earlier during fatigue ($p \leq .09$). Step-wise multiple regression suggested that the knee may be the primary site of force attenuation following fatigue. During fatigue, biodynamical compensations in the mechanical properties of the knee extensor musculature, as evidenced by differences in knee kinematics and muscle activation times, may occur to enhance knee stability.

Key Words: *run and rapid stop, muscle action, biodynamics*

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Over the last four decades, the interest and participation of women in sports has increased. Concurrently, the incidence of injury among female athletes has also increased. Knee and ankle injuries have been reported to occur with a disproportionately greater incidence among female athletes than their male counterparts (4,31). Injuries related to overuse, such as patellar tendinitis, patellofemoral stress syndrome, and fatigue fractures, are becoming more apparent among female athletes. In sports such as volleyball and basketball, the transition from running to jumping or to a stance position requires well-controlled muscular activity by the athlete (19). During the stance phase of sports movements, the lower extremity undergoes the largest and most repetitious forces (3,16,19,23). Fatigue may promote altered biodynamical characteristics during the stance phase to enhance joint stability and protect inert internal tissues, such as ligaments (2,10,30,32). During the stance phase, shock absorption is achieved through muscle stiffness, bony deformation, joint motion, and cartilage compression. When the stabilizing influence of muscle is not present, inert internal tissues such as cartilage and ligaments become more vulnerable to abnormal forces (29,32). These stresses and the resulting strains in muscle, ligaments, joints, and bones may lead to structural and functional adaptations or even tissue destruction (3,19,29). Excessive force magnitudes and/or repetitious forces may surpass the capacity and recovery limits of these tissues and result in disruption, or irritation followed by secondary disruption (13,22,29). This may partially explain the numerous reports of lower extremity injury among female basketball and volleyball players (11,12,14,15,17, 25,26). Ferretti et al reported that the knee was the most frequent site of injury among volleyball players (12). Gerberich reported that jumping, landing, and twisting upon ground contact accounted for 63% of all lower extremity injuries and 61% of total knee injuries among volleyball players (14). This study also reported a predominance of ligamentous injuries in males and patellofemoral pain in females. Schafle reported that the ankle was the most frequently injured site, comprising 17% of the total injuries of 1,520 participants at a national volleyball tournament (26). Ray et al reported that ankle injuries comprised 55% of the total injuries sustained by 2,716 female high school basketball players during one competitive season (25).

To adequately condition and rehabilitate the female athlete, information regarding biodynamical factors of athletic performance need to be obtained. In addition, the effect of fatigue on the motor control strategies implemented during the performance of functional tasks needs to be evaluated.

Purpose

This study was performed to determine: *1*) normal lower extremity kinematics and muscle activity during the landing phase of a run and rapid stop, *2*) the effect of general lower extremity fatigue on lower extremity kinematics and muscle activity during the landing phase of a run and rapid stop, and *3*) the relationship of lower extremity joint position and velocity to peak passive vertical ground reaction force and peak braking (posterior) force during the landing phase of a run and rapid stop.

METHODS

Subject Groups and Fatigue Method

Nineteen University of Kentucky women's volleyball or basketball players ($\bar{X}$ age 20.8 ± 1.8 years, $\bar{X}$ weight 71.7 ± 6.9 kg, $\bar{X}$ height 174 ± 5 cm) participated in the study. All subjects provided informed consent according to federal and university guidelines. None of the athletes exhibited lower extremity problems at the time of the study. The dominant lower extremity of each subject, as determined by jump preference, was tested. Following warm-up, each subject was asked to perform three trials of a run and rapid stop. A general lower extremity fatigue was induced via an uphill treadmill walking protocol. Each subject walked at 1.35 m/sec on a 10% grade for 3 minutes. Every minute thereafter, the grade was raised 2%. The cessation of the fatigue protocol occurred when the subject stated that they could not continue. Following this protocol, three trials of a run and rapid stop were repeated. Figure 1 depicts run and rapid stop performance and stance lower extremity instrumentation.

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Kinematic and Kinetic Analysis Instrumentation

Performance of each run and rapid stop maneuver was videotaped with three 200-Hz cameras (Model HVRB-2000, NAC, Inc. Tokyo, Japan). Retroreflective markers approximated the position of the shoulders (acromion process), hips (greater trochanter), knees (midlateral joint line), ankles (anterior joint line), and feet (dorsal third ray). The video data were collected using the Expert Vision software package (Motion Analysis Corporation, Santa Rosa, CA) on a microcomputer (Model 3/260, Sun Microsystems, Inc., Mountain View, CA). Two cameras were located anterior to the subject on each side of the runway, and a third camera was positioned to provide a sagittal view of the subject. Each camera was strategically placed so all retroreflective markers could be viewed by at least two cameras throughout each run and rapid stop trial, enabling three-dimensional kinematic analysis. The representation of each marker in at least two cameras is a requirement of the Direct Linear Transformation procedure (1,27). Calibration of the three-dimensional space and placement of the anatomical reference markers were performed according to the Direct Linear Transformation procedure (1,27). Dominant lower extremity landing impact forces were collected from a force platform (Model 9261A, Kistler Instrumentation Corp., Winterthur, Switzerland) at a sampling rate of 2,000 Hz, with amplified analog signals input to an analog-to-digital board (Model DT-2821-F-16SE, Data Translation, Marlboro, MA) and stored on a PC-AT type computer (Northgate Computer Systems, Inc., Plymouth, MN). Figure 2 depicts representative peak passive vertical ground reaction force and peak braking force following landing heelstrike of the run and rapid stop.

Electromyographic Analysis Instrumentation

Following alcohol-swab skin preparation, each subject had silver-silver chloride surface electrodes with on-site preamplifiers (Model D-100, Therapeutics Unlimited, Iowa City, IA) placed over the central muscle belly of the following muscles of the dominant lower extremity: *1*) rectus femoris, *2*) vastus lateralis, *3*) biceps femoris, *4*) medial hamstrings, and *5*) medial gastrocnemius. Prior to run and rapid stop performance, a manual muscle test was performed for each muscle to record electromyographic (EMG) activity during a maximal voluntary contraction (5). An EMG "quiet file" was also recorded for each muscle to determine baseline EMG activity. All EMG data were collected synchronously with

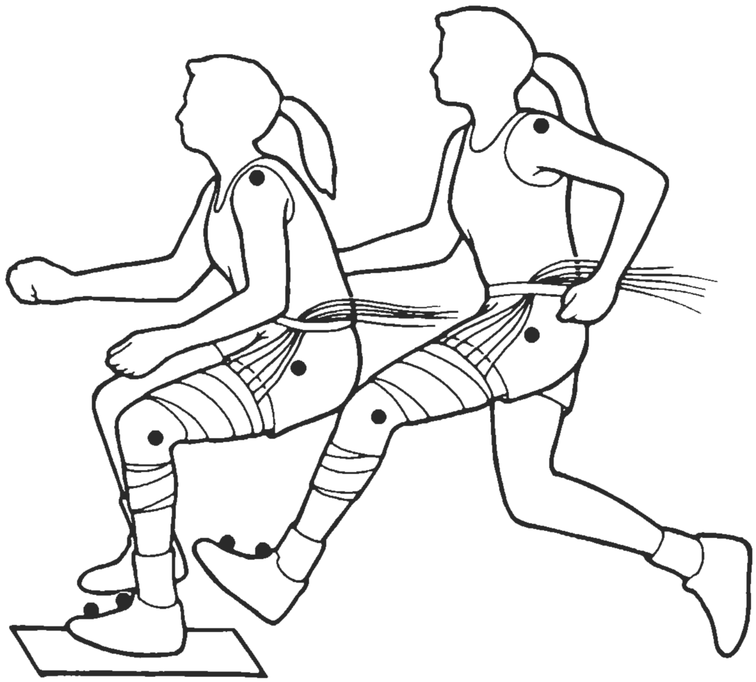

FIGURE 1. *Subject landing on force platform during the run and rapid stop maneuver with reflective markers in place and electrode leads secured.*

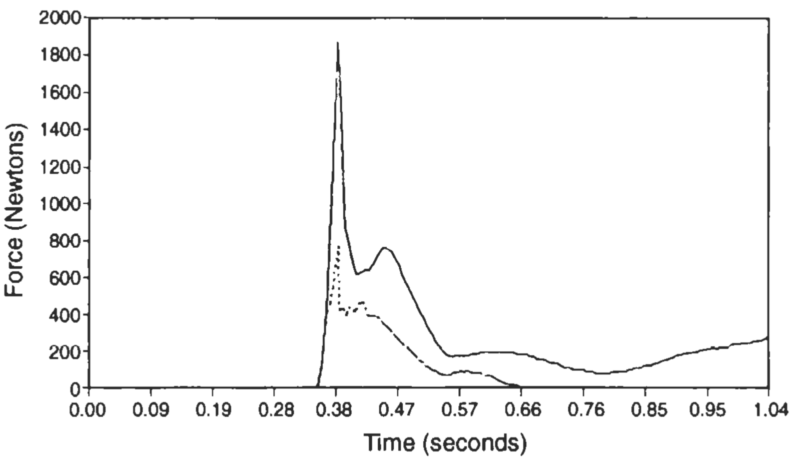

FIGURE 2. *Representative peak passive vertical ground reaction force (solid line) and peak braking ground reaction force (dotted line).*

force and video data. The EMG data were sampled at 2,000 Hz, with an eight-channel EMG amplifier (Model EMG-67EMG Amplifier Processor, Therapeutics Unlimited, Iowa City, IA) input to the same analog-to-digital board described earlier and stored on a PC-AT type computer.

The onset of muscle activity for each trial was determined using Asyst v.2.1 software (Macmillan Software Co., New York, NY) and the following protocol (18): First, a threshold voltage for each muscle onset was calculated from the "quiet EMG file." The mean and standard deviation of the rectified signal were determined. The threshold voltage (V_o) required for muscle onset was then calculated from the equation:

$$V_o = \bar{X} + 3 * SD$$

The onset of muscle activity was evaluated by comparing discrete data point values (V_i) in a point-by-point fashion to the threshold voltage. When a discrete data point value was found such that $V_i > V_o$, a 25-msec (50-point) window of data immediately adjacent to the point was evaluated. When the mean voltage within the window exceeded V_o, the initial data point value was considered to represent the onset of muscle activity. When the mean voltage within the window was less than V_o, the data point value was considered to be a random spike or artifact and the next data value was evaluated. After all of the muscle activity onset values were determined, the window of active EMG that corresponded most temporally with landing heelstrike was determined. This procedure was repeated for each muscle in each trial.

Statistical Methods

Descriptive statistics, including means and standard deviations, were obtained for all variables. A repeated measures analysis of variance (ANOVA) design was used to evaluate the effect of fatigue on kinetic/kinematic variables. Paired, two-tailed *t* tests were performed to evaluate the unfatigued vs. fatigued effects on individual muscle activity onset prior to heelstrike.

Stepwise maximum R^2 multiple regression was performed with dominant hip, knee, and ankle positions and velocities [at peak passive vertical ground reaction force and peak braking (posterior) force] as independent variables and peak passive vertical ground reaction force and peak braking (posterior) force as dependent variables. Dynamic maneuvers, such as a run and rapid stop, reportedly demonstrate a significant causal relationship between kinematic variables at the hip, knee, and ankle joints and peak ground reaction forces (7,8). A nontraditional probability level of $p < .1$ was chosen for all statistical procedures to demonstrate general tendencies or trends toward statistical significance (21).

RESULTS

Mean time until volitional cessation of the fatigue protocol was 14.59 ± 3.6 minutes (range 11.3–23 minutes). Table 1 shows dominant lower extremity peak passive vertical ground reaction force; peak braking force; joint position and angular velocity of the hip, knee, and ankle at time of peak passive vertical ground reaction force; approach velocities; and time from landing heelstrike to maximum knee flexion for the unfatigued and fatigued conditions. The probability value (p) for each parameter is also presented.

Step-wise maximum R^2 multiple regression of all dominant lower extremity kinematic variables found unfatigued/fatigued regression coefficients for ankle angle (−776.4/5,254.1), knee angle (146.7/−1,781), and knee velocity (50.4/123) at landing to be the best predictors of peak passive vertical ground reaction force [($R^2 = .388$, C(P) = 2.2, $F = 3.4$, $p \leq .04$)/($R^2 = .764$, C(P) = 2.1, $F = 17.8$, $p \leq .0001$)]. Mallow's C(P) statistic is a criterion for discriminating between regression models. This statistic considers both variance and bias in helping to select a regression model (lowest value) that best controls for overfitting or underfitting (21). The multiple regression models of maximum R^2 and minimal C(P) were:

Unfatigued peak passive vertical ground reaction force = 1,842 + −776.4 (ankle angle) + 146.7 (knee angle) + 50.4 (knee velocity)

Fatigued peak passive vertical ground reaction force = −2,703 + 5,254.1 (ankle angle) + −1,781 (knee angle) + 123 (knee velocity)

Multiple regression did not find unfatigued/fatigued regression models that were predictive of peak braking force.

Table 2 shows the means and standard deviations of the onset of muscle activation prior to landing heelstrike during the run and rapid stop for the unfatigued and fatigued conditions and the probability value for each parameter.

During the fatigued run and rapid stop trials, the onset of muscle activation of the rectus femoris, vastus lateralis, biceps femoris, and medial hamstring muscles tended to occur later than during the unfatigued run and rapid stop trials ($p \leq .08$). This occurred in the absence of differences between unfatigued/fatigued approach velocities, peak passive vertical ground reaction force, peak braking force, joint position, or joint velocities at time of peak passive vertical ground reaction force ($p > .1$). Concurrently, maximal knee flexion angle tended to occur earlier ($p \leq .09$) during the fatigued run and rapid stop trials than during the unfatigued run and rapid stop trials.

	Unfatigued		Fatigued		p
	X̄	SD	X̄	SD	
Approach velocity	4.15 m/sec	0.57	3.92 m/sec	0.74	.45
PPVGRF	2.35 BW	0.45	2.97 BW	0.5	.37
PBF	1.35 BW	0.5	1.57 BW	0.55	.48
Hip angle (PPVGRF)	49°	15.4	48°	18.3	.53
Hip velocity (PPVGRF)	160°/sec	160	183°/sec	114	.72
Knee angle (PPVGRF)	36°	11.4	35°	14.3	.60
Knee velocity (PPVGRF)	469°/sec	143	503°/sec	172	.68
Ankle angle (PPVGRF)	51°	10.3	52°	14.3	.41
Ankle velocity (PPVGRF)	160°/sec	229	74°/sec	160	.77
Landing heelstrike time to maximum knee flexion	.235 sec	0.07	.217 sec	0.06	<.09

PPVGRF = Peak passive vertical ground reaction force.
PBF = Peak braking (posterior) force.
BW = Body weight.

TABLE 1. *Means, standard deviations, and p values of selected parameters.*

	Unfatigued		Fatigued		p
	X̄	SD	X̄	SD	
Rectus femoris	−88.8	60	−55.9	34	<.01
Vastus lateralis	−121.3	81.6	−81.4	37.1	<.06
Biceps femoris	−114.9	83	−87.1	77.8	<.08
Medial hamstrings	−155.1	77.7	−115.6	77.3	<.08
Medial gastrocnemius	−91.2	60.6	−77.5	54.4	.2

TABLE 2. *Means, standard deviations, and p values of muscle activity onset with respect to landing heelstrike (in msec).*

DISCUSSION

The peak passive vertical ground reaction force generated at landing heelstrike is transmitted proximally through the lower extremity's musculoskeletal system. The magnitude and repetitiveness of these forces may be related to overuse injuries, degenerative changes in joints, and low back pain (20,29). Nigg suggested that peak impact forces during running decrease as knee flexion angle at touchdown increases (22). Greater knee flexion angles during the stance phase of demanding functional activities, such as cutting maneuvers, have been reported to increase the effectiveness of the thigh musculature as dynamic stabilizers of the knee to prevent excess shear forces (2,30).

Unlike running or a run-land-vertical jump progression, the run and rapid stop is terminated by a rapid stoppage of the movement as the eccentric action of the quadriceps femoris, hamstrings, and gastrocnemius-soleus muscles decelerate the horizontal velocity of the body

(6,9,16). Movement patterns that terminate with passive vertical/braking ground reaction forces and eccentric muscle actions may present different biodynamical characteristics than cyclical, continuous movement patterns, which present a succession of concentric-eccentric-concentric lower extremity muscle action (9,29). The biodynamical characteristics of primary importance, as determined by this study, may be the onset of muscle activation and the timing of maximal knee flexion.

The central nervous system manipulates the mechanical properties of muscle to enhance the performance of differing maneuvers (9). Our previous findings noted that muscle activation occurs earlier during the performance of running and a run-land-vertical jump progression in the presence of fatigue (28). Maneuvers such as running or a run-land-vertical jump progression are greatly dependent upon the spring-like properties provided by a relatively stiff (positive stiffness) muscle. This enhances the absorption, storage, and release of elastic energy. Muscle stiffness is characterized by resistance to external loads on a muscle or muscle group as it deforms. Fatigue has been reported to result in an earlier onset of lower extremity muscle activation for each of these maneuvers (9,28).

In contrast, the run and rapid stop maneuver is greatly dependent upon the shock absorption or damping properties of muscle. Damping is characterized by resistance to the speed of deformation. Lower muscle stiffness (negative stiffness) present during this type of maneuver is reportedly caused by submaximal alpha motor neuron activation, the suppression of motor neuron discharge frequency, or both, resulting in a segmented EMG signal (9). These findings may partially explain the results of our study. Perhaps the delayed onset of muscle activation found during fatigue for the rectus femoris, vastus lateralis, biceps femoris, and medial hamstring muscles and the earlier achievement of maximal knee flexion are compensations to enhance shock absorption/damping, thereby protecting the knee. Previous studies have identified the knee extensors as important dynamic restraints against excessive anterior shear forces of the femur on the tibia (2, 30). These same studies found that anterior-cruciate-ligament-deficient subjects presented increased knee flexion angles during the stance phase of a side-step or cross-over cut maneuver to enhance the dynamic stabilizing capability of the knee extensors (2,30).

Since the run and rapid stop maneuver occurs primarily in the sagittal plane, the need for the biceps femoris and medial hamstring muscles as dynamic medial or lateral rotary stabilizers is reduced. The medial hamstring muscles and the long head of the biceps femoris muscle act across both the hip and knee. Since each originates from the ischial tuberosity of the pelvis, each can effectively act as a dynamic trunk stabilizer by controlling trunk flexion.

Maximal knee flexion angle tended to occur earlier during the fatigued run and rapid stop trials than during the unfatigued run and rapid stop trials.

General lower extremity fatigue, as produced by our protocol, may also promote changes in ankle and knee deceleration strategies (24). Step-wise, maximum R^2 multiple regression demonstrated an extreme reversal in the sign and magnitude of the regression coefficients of ankle and knee angle as predictors of peak passive vertical ground reaction force during the fatigued condition. During the unfatigued condition, as ankle angle at peak passive vertical ground reaction force increased, an attenuation effect (−776.4) on this force occurred. During the fatigued condition, as ankle angle at peak passive vertical ground reaction force increased, an intensifying effect (5,254.1) on this force occurred. In contrast, during the unfatigued condition, as knee angle at peak passive vertical ground reaction force increased, a lesser intensifying effect (146.7) on this force occurred, while an attenuation effect (−1,781) on this force occurred during the fatigued condition. This finding suggests a relative reversal of roles as peak passive vertical ground reaction force attenuators at the knee and ankle during the fatigued condition, with the knee playing the primary role as peak passive vertical ground reaction force attenuator. This may further explain the presence of later onset of muscle activation and the earlier occurrence of maximal knee flexion during fatigue when performing the run and rapid stop maneuver.

SUMMARY

Movement patterns that terminate with passive vertical/braking ground reaction forces and eccentric muscle actions may demonstrate biodynamical characteristics that differ from more cyclical, continuous movement patterns, which present a succession of concentric-eccentric-concentric lower extremity muscle activation. This study found that run and rapid stop performance following fatigue showed trends toward later rectus femoris, vastus lateralis, biceps femoris, and medial hamstrings onset of muscle activation and earlier occurrence of maximal knee flexion. Differences in the onset of muscle activation and the occurrence of maximal knee flexion

The run and rapid stop maneuver is greatly dependent upon the shock absorption or damping properties of muscle.

may occur to enhance damping/shock absorption and knee stabilization in the presence of fatigue. Further studies that include training periods for test maneuvers and a fatigue method that more closely approximates specific sports performance are recommended. JOSPT

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