Alterations in Peak Ground-Reaction Force During 60-cm Drop Landings Caused by a Single Session of Repeated Wingate Anaerobic Tests

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Context: Lower extremity injury is prevalent among individuals participating in sports. Numerous variables have been reported as predisposing risk factors to injury; however, the effects of muscle fatigue on landing kinetics are unclear. Objectives: To investigate the effects of a single session of repeated muscle fatigue on peak vertical ground-reaction force (GRF) during drop landings. Design: Mixed factorial with repeated measures. Setting: Controlled laboratory. Participants: 10 female and 10 male healthy recreational athletes. Intervention: Subjects performed 3 fatigued drop landings (60 cm) after four 20-s Wingate anaerobic tests (WATs) with 5 min of active recovery between fatigued conditions. Main Outcome Measures: Kinetic data of peak forefoot (F1) force, peak rear-foot (F2) force, and anteroposterior (AP) and mediolateral (ML) forces at both F1 and F2. Results: A significant main effect was observed in the nonfatigued and fatigued drop landings in respect to peak F2 force. The greatest significant difference was shown between the first fatigued drop-landing condition and the last fatigued drop-landing condition. No significant difference was observed between genders for all GRF variables across fatigue conditions. Conclusion: A single session of repeated conditions of anaerobic muscle fatigue induced by WATs caused an initial reduction in peak F2 force followed by an increase in peak F2 force across conditions. Muscle fatigue consequently alters landing kinetics, potentially increasing the risk of injury.

Keywords: muscle fatigue, landing performance, lower extremity

Lower extremity injuries are common in sports and are caused by the interaction of modifiable and unmodifiable risk factors. Conceptualizing modifiable and unmodifiable risk factors enables clinicians and injury researchers to understand and propose evidence-based injury-prevention interventions.1,2

Anterior cruciate ligament (ACL) knee injuries are among the most common lower extremity injuries.1,3–5 Sports medicine professionals manage concerns related to noncontact ACL and lower extremity musculoskeletal injury risk and injury prevention through a multifaceted approach. Biomechanical analysis provides quantifiable data on the force acting on the body to help explain injury mechanisms and mechanics.

During ambulation and athletic performance, the body attenuates variable magnitudes of ground-reaction force (GRF), specifically from landing.6–9 Landing performance has been observed to vary by gender, as demonstrated by different landing strategies and different neuromuscular responses.10–13 The female neuromuscular response has been shown to be a predisposing factor to lower extremity injuries, including stress fractures and ACL tears.11,14

Additional variables such as muscle fatigue add to the complexity of attenuating GRF loads. GRF has been shown to decrease with lower extremity muscle fatigue due to increases in angular velocity at the hip and knee,15 which alter usual landing strategies. Lower extremity muscle fatigue could result in undesirable movement patterns such as a significant increase in knee flexion and dorsiflexion, causing additional stress to the ACL and surrounding tissue.2,15–17 Examination of biomechanical variables while landing under fatigued conditions is needed to increase our understanding of lower extremity injury and assist in the development of injury-prevention programs and interventions.

Muscle fatigue results in an inability to sustain or maintain muscle contractions at a given force production.18–21 Fatigue can be both central and peripheral in nature, although both types of fatigue affect landing mechanics by altering muscle stiffness and execution of landing due to inadequate force production. Therefore, adaptations in landing mechanics while fatigued predispose athletes to lower extremity musculoskeletal injuries. Recent research19,20,22 has focused on the effect of...
muscle fatigue on task-specific skills and the interactions of exercise-induced fatigue, which has provided insight into injury prevention and management. Further research examining the interaction of muscle fatigue and biomechanical variables during landing tasks is needed to gain a greater understanding of lower extremity injury mechanisms.

Various protocols have been used to investigate exercise-induced fatigue responses on muscle force production and neuromuscular activation. A 30-second Wingate anaerobic test (WAT) has been the standard modality to measure anaerobic responses such as the fatigue index that measures a decline in peak power. The standard duration of a WAT is 30 seconds; however, 20 seconds has also been used and shown to be a valid alternative to the 30-second test to encourage participant compliance. The WAT has been used as a protocol to induce muscle fatigue and examine its effect on landing mechanics. Additional studies with repeated bouts of the WAT to mimic athletic activity patterns will provide greater understanding of injury mechanisms of the knee. The purpose of this study was to investigate the effects of repeated muscle fatigue on GRF during drop landings and determine if there are gender differences. We hypothesized that muscle fatigue would alter landing kinetics and potentially increase the risk for lower extremity injury.

Methods

Design

Participants performed drop landings under 5 experimental conditions. The first condition required them to perform 5 nonfatigued drop landings (control) from a 60-cm platform, followed by 4 fatigued conditions that consisted of a 20-second WAT followed by 2 drop landings between bouts. Participants performed the WAT by pedaling an ergometer bicycle with both legs in a seated position using pedal toe straps. Before the experimental condition was administered, a 5-minute warm-up was performed on the cycle between 60 and 70 rpm with 1 kg of resistance. After the warm-up, each participant performed the 5 nonfatigued drop landings and then the first fatigued bout. Each fatigued condition was followed by 2 drop landings (60-cm) onto a force platform with 5 minutes of active rest between that included 4 minutes of cycling at the warm-up intensity.

Independent variables were fatigue condition and gender. Dependent variables included peak vertical forefoot (F1) GRF, peak vertical rear-foot (F2) GRF, anteroposterior (AP) force at F1, AP force at F2, mediolateral (ML) force at F1, and ML force at F2. The F1 and F2 variables were scaled to the number of body weights (BW) for each participant for practical relevance.

Participants

Ten female (22.5 ± 0.85 years) and 10 male (24.1 ± 2.6 years) recreational athletes from a university-student population volunteered for this study. Recreational athletes were defined as individuals who had participated in a jumping sport such as basketball or volleyball at least 3 times per week within the last 3 months but were not members of any intercollegiate athletic team. The number of participants and drop-landing trials used in this study were similar to those found in previous research.

Participants attended an information session 1 week before the onset of data collection to orient them to the experimental protocol, answer all questions, and review the informed consent. The experimental session included collection of the signed consent form, administration of a medical-history injury form, and completion of a lower extremity orthopedic physical examination to assess joint integrity. Participants were required to have been free of lower extremity injury for at least 6 months before data collection and have no history of ACL injury, ankle instability, or cardiovascular or pulmonary illness, as screened by the health questionnaire and an orthopedic physical examination performed by an athletic trainer. Demographic data of age, weight, and height were recorded. Participants were instructed to refrain from any form of exercise and alcohol and caffeine consumption for 24 hours before data collection and were excluded if they did not adhere to the criteria. The study was approved by the institutional review board, and all participants provided consent before data collection.

Procedures

Participants performed drop landings from a 60-cm platform onto a force plate installed flush with the floor surface. The force plate was located 20 cm from the front of the 60-cm platform. Participants landed with their bare feet on the force plate and floor to eliminate shoe interaction and changes in GRF due to shoe cushioning effects and were allowed to practice the drop landings to become comfortable with the protocol. They landed with their right foot on the force plate and the other foot beside it. Leg dominance was determined by asking them to identify the leg with which they would prefer to kick a ball. All participants reported right-leg dominance.

To avoid any coaching effect, participants were instructed to land how they would normally land if they had to drop from any given height to ensure their normal landing mechanics. They dropped when given the instructions “ready and drop.” The ready command was given once participants had crossed their arms in front of their body and their dominant foot was hanging off the platform. Each participant performed 2 drop landings after each fatigue condition with 30 seconds of rest after each drop landing to reduce muscle-fatigue recovery. The 30-second recovery allowed each subject to perform the drop landings safely and adequately. A stopwatch was used to control for time.

Drop landings were deemed acceptable if the entire foot was in contact with the force plate, balance was
maintained, and the participant remained on the force plate for a minimum of 2 seconds. Unacceptable trials were repeated as soon as possible during the fatigued drop landings.

Fatigue was induced by a 20-second WAT. Before the test was administered, participants practiced the protocol for several seconds to ensure that they could perform it correctly. The fatigue protocol required participants to pedal as hard as possible with no resistance until a cadence was reached. Once they reached a high cadence (after several seconds), they pushed a button on the handlebars that instantly added a resistance of 7.5% of their body weight for 20 seconds as verbal encouragement was given to promote maximal effort. Immediately after the fatigue bout, participants were instructed to promptly remove their shoes and perform the drop landings. Peak power, average power, and fatigue index were collected to monitor fatigue and effort.

Immediately after the WAT, participants were asked to rate their rating of perceived exertion using the Borg scale and to report any symptoms of headache, dizziness, or other adverse symptoms due to the fatigue condition.

Instrumentation
GRF was collected by 9281C Kistler force plate (Kistler Instruments Corp, USA) and amplified with an external 8-channel 9865B change amplifier (Kistler Instruments Corp). The GRF data were analyzed with Peak Motus Software 8.0 (Peak Performance Technologies Inc, USA). Analog data were sampled at 8500 Hz and filtered using an eighth-order low-pass Butterworth filter with a cutoff frequency of 293 Hz to remove oscillation from the landing that had ~833 Hz resonant frequency.

The WAT was collected by a Monark Ergomedic 894E Peak bike (Monark, Sweden) with Windows-based Monark Anaerobic software (Monark, Sweden) to determine fatigue characteristics.

Statistical Analysis
The means and standard deviations were calculated for the drop landings for each experimental condition. Independent and dependent variables were used in a mixed-factor analysis of variance (ANOVA) with fatigue as the repeated measures for the dependent variables to analyze the equality of means. Dependent variables were treated separately to test within-condition effects, between-conditions effects, and interactions with an a priori alpha of .05. Effect sizes and power were calculated for all analyses.

Pairwise comparisons were used to identify differences within all the fatigue conditions using a Bonferroni adjustment ($P = .01$). Data were analyzed using SPSS statistical software, version 17.0 for Windows (SPSS Inc, Chicago, IL).

Results
Descriptive data were collected for all participants during the WAT to monitor fatigue. Peak power was significantly greater in men ($633.34 ± 120.30$ W) than in women ($373.23 ± 80.58$ W), and both male ($45.36% ± 8.29%$) and female ($42% ± 10.21%) participants demonstrated similar overall percentage power drop after fatigued bouts (Table 1). Significant differences were observed within and between all fatigue conditions ($P < .05$), except the first bout, compared with baseline.

The mean rating of perceived exertion was used to monitor fatigue and effort during the fatigue conditions. The rating of perceived exertion was similar among participants who reported the fatigue bouts as hard and very hard across all fatigue conditions with a high level of exertion ($16.23 ± 2.06$).

Gender and GRF
Data revealed significant differences in GRF for F2 between fatigue conditions (Figure 1), but not by gender. Gender did not influence peak-force magnitudes during drop landings for any of the fatigue conditions. Peak GRF values for men ($7.84 ± 1.5$ BW) were nearly identical to those recorded for women ($7.82 ± 2.2$ BW) in the nonfatigued condition.

AP and ML Force
Results of this study revealed no significant differences between gender for AP and ML force at F1 and F2 for either nonfatigued or fatigued conditions. AP and ML forces were measured to determine the relationship of changes in peak force. ML forces at F1 and F2 were not statistically significant ($P > .05$); however, a high degree of variability was observed among participants, resulting in large standard deviations. Variable ML peak forces were observed among participants performing fatigued landings (Table 2).

<p>| Table 1 Peak Power, Mean Power, and Power Drop, Mean ± SD |
|----------------|------------------|------------------|------------------|</p>
<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Peak power (W)</th>
<th>Mean power (W)</th>
<th>Power drop (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Men</td>
<td>10</td>
<td>633.34 ± 120.30</td>
<td>504.68 ± 106.09</td>
<td>45.36 ± 8.29</td>
</tr>
<tr>
<td>Women</td>
<td>10</td>
<td>373.23 ± 80.58</td>
<td>303.35 ± 67.24</td>
<td>43.00 ± 10.21</td>
</tr>
<tr>
<td>Overall</td>
<td>20</td>
<td>503.29 ± 100.29</td>
<td>404.02 ± 86.67</td>
<td>44.18 ± 9.23</td>
</tr>
</tbody>
</table>
Wingate Tests and Ground-Reaction Force

Discussion

We used the WAT to produce exercise-induced fatigue to identify alterations in GRF during drop landings by fatigue level and gender. Surprisingly, there were no significant gender differences in peak-force magnitudes during the fatigued drop landings. This result contrasts with those reported in the literature that indicated landing differences between males and females. Peak GRF was high for both genders and can be attributed to landing barefoot on the force plate.

Landing differences between genders have been attributed to neuromuscular responses. These neuromuscular responses are usually altered immediately after muscle fatigue. Neuromuscular exercise-induced fatigue is the integration of central and peripheral processing of the nervous system and skeletal muscle, resulting in a reduction of muscle work. However, in our study, muscle function after fatigue was equally altered for both genders, and although differences in landing strategies have been reported between genders elsewhere, our data did not reveal any differences. However, we casually observed an interesting trend that warrants further examination. Across both genders, muscle fatigue led to an initial reduction in GRF, followed by an increase in GRF as fatigue steadily progressed. Given the dearth of literature on this phenomenon, we will examine this further in future studies.

GRF variables determine magnitude of force but do not quantify the joint positioning that created those forces. Kinematic analyses are required to quantify and explain changes in GRF. Gender differences may have been revealed with kinematic analyses and may have further explained observed changes in GRF after each subsequent fatigued bout, but measuring this was not feasible due to instrumentation and equipment constraints. The observed reduction in GRF followed by an increase in GRF as fatigue increased can be explained by the role of the musculature in attenuating GRF. During early trials, an increase in sagittal- and frontal-plane movement was observed on video.

More than three-fourths (76%) of participants demonstrated higher peak force for the second drop landing than for the first, indicating a probable increase in fatigue even within the fatigued condition. Our research design was such that the mean and standard deviation were calculated for all trials in a condition. However, we found it interesting that recorded values for the second trial were consistently much higher than for the first trial. Therefore, reporting the second trial value instead of averaging the trials within each condition might be a better way to report fatigue data in future studies.

Table 2 Analysis for Ground-Reaction Force (BW) Across All Conditions and Between Genders

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>P</th>
<th>$\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forefoot force</td>
<td>3.51</td>
<td>0.90</td>
<td>.314</td>
<td>.257</td>
</tr>
<tr>
<td>Rear-foot force</td>
<td>8.35</td>
<td>2.35</td>
<td>.003*</td>
<td>.634</td>
</tr>
<tr>
<td>AP force at forefoot</td>
<td>6.21</td>
<td>2.03</td>
<td>.172</td>
<td>.330</td>
</tr>
<tr>
<td>AP force at rear foot</td>
<td>1.51</td>
<td>2.38</td>
<td>.427</td>
<td>.214</td>
</tr>
<tr>
<td>ML force at forefoot</td>
<td>0.1</td>
<td>1.04</td>
<td>.942</td>
<td>.047</td>
</tr>
<tr>
<td>ML force at rear foot</td>
<td>4.62</td>
<td>9.95</td>
<td>.305</td>
<td>.261</td>
</tr>
</tbody>
</table>

Abbreviations: AP, anteroposterior; ML, mediolateral; BW, body weight.

Figure 1 — Peak rear-foot vertical ground-reaction force by fatigue condition. *Significant difference between fatigued and non-fatigued conditions, $P < .05$. 

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Data indicated that with the onset of muscle fatigue, participants increased the time over which the force was applied from initial contact to heel contact. This interpretation was based on the measured time between F1 and F2 contact and was an additional analysis used to quantify the initial reduction identified in peak GRF because 3D kinematic analyses were not used.

The initial reduction of peak forces that we observed is advantageous in reducing lower extremity impact injuries such as stress fractures, but it may increase soft-tissue injury as landing force is attenuated by muscle and other tissues. Kinematic analysis has shown that untrained females land with an increased valgus angle at the knees, resulting in altered time between initial contact and heel contact with inadequate joint positioning. Even though this landing strategy accomplishes GRF reduction, it may predispose to or even cause more lower extremity injuries than would high-impact forces alone. This increased valgus-angle landing strategy usually resulted in decreased peak force after the first fatigued bout, followed by a general progression of increased force with each subsequent landing trial. The increase of peak force (F2) occurring after each fatigue protocol can be attributed to increased landing stiffness.

Stiff landings result from altered joint positioning of the trunk and lower extremity and are generally caused by reduced flexion of the trunk and knees. This neuromuscular adaptation allows for the performance of fatigued landings even when muscles are incapable of producing a maximal contraction or sufficient power output to perform a task. Fatigued muscle responds by recruiting smaller motor neurons and recruiting different muscles, which thereby influence neuronal synaptic transmission, firing rate and frequency, conduction velocity, and sequence of muscle contractions. This neuromuscular alteration accommodates the demand of repeated muscle contractions. Without this adaptation, fatigue participants would collapse during landing. Therefore, a certain magnitude of joint stiffness is expected during fatigued landings and is a neuromuscular requirement.

Increases in ML force at F1 may indicate movement in the frontal plane at contact that affected overall joint positioning and increased lower extremity muscle activity. These alterations influenced landing performance and increased stress to the lower extremity, specifically to the ACL. Changes in these variables could indicate that significant AP and ML forces at the knee and hip may have occurred to provide the necessary stiffness to execute a landing while fatigued.

Although there are various fatigue protocols, with some deemed more functional than others and more readily generalizable to an active athlete population, researchers have identified modifiable and unmodifiable risk factors associated with injury. Recently, attention has been focused on modifiable risk factors such as neuromuscular control, biomechanical factors, and fatigue during landing and cutting. Researchers have used the WAT for exercise-induced fatigue. Jumping and running protocols encompass the elastic component of tissue, and although the WAT does not, both involve concentric and eccentric work. The major limitation of using a jumping and running fatigue protocol is that it introduces variability due to individual skill on the task, whereas the WAT is more tightly controlled while still incorporating large muscle groups associated with jumping and running.

Establishing fatigue criteria is difficult regardless of protocol. The criterion is a measure expressed as a percentage of work capacity, such as 50% or 80% of maximal force output, which is then compared with a certain measureable skill, such as GRF during landings, to determine if there were differences based on fatigue or failure of a specific task. Observed changes are accounted as fatigue effects. Therefore, in any fatigue protocol, the question of whether the protocol effectively induced fatigue remains open to interpretation since other factors may influence performance.

The WAT is a well-established exercise test that measures anaerobic capacity and produces a significant degree of fatigue during test performance, as evidenced by the percentage decrease in peak power at the end of the test. Although no standard for percentage of power drop has been established to indicate fatigue, participants recorded a 44% decrease in power. These results are consistent with subsequent WAT’s performed with 3 minutes and 20 seconds of recovery. Wilson et al reported a power decline of 48% to 56% across participants who performed repeated conditions of the WAT on different days and cycling positions. Our results are also comparable to normative data of power declines reported for men (47% ± 7.6%) and women (42% ± 7.9%) in NCAA Division I sports.

Fatigue can also be assessed by determining subjects’ levels of exertion. Participants rated their average exertion level at 16, which indicated very hard exertion. When the WAT was performed with maximal effort, a significant degree of fatigue resulted. To ensure fatigue, 4 conditions of the WAT were administered with 5 minutes of active rest. Theoretically, participants could have recovered within the 5-minute rest period; however, fatigue effects have been shown to last more than 40 minutes. Therefore, it was assumed that participants were fatigued during the drop-landing protocol and that changes in peak GRF were the result of fatigue.

Clinical Relevance

Noncontact ACL and lower extremity injuries occur at high rates in sports, with the highest percentage occurring among females. In the literature, it is generally accepted that females’ landing strategies predispose them to noncontact ACL injuries. The challenge is to create a research protocol that exposes athletes to the same stress and level of performance as their particular sport without causing injury.

Researchers have identified modifiable and unmodifiable risk factors associated with injury. Recently, attention has been focused on modifiable risk factors such as neuromuscular control, biomechanical factors, and fatigue during landing and cutting. Understanding how the body responds to landing in a fatigued state is vital since athletes participate in sports while fatigued and fatigue has been shown to be a
precursor to many overuse injuries. Performance alterations demonstrated during specific functional tasks are of great importance to understanding injury mechanisms. Alterations observed during fatigued landings provide valuable insight as to the physiological and neuromuscular adjustments employed during skill performance before task failure or injury occurs. However, these adjustments can be counterproductive and predispose the body to injury. Identifying what neuromuscular factors influence specific task failure, rather than quantifying force output to establish fatigue, is the desired direction for understanding functional task performance and fatigue.

Overall functional strength and neuromuscular control delay muscle fatigue. Therefore, maximal functional strength along with proper education on how to land is critical to reduce overuse injuries. Education and landing coaching have been effective in reducing injury. Prevention programs have implemented landing and jump training to encourage a landing strategy that decreases force and maintains adequate joint stiffness by increased knee and hip flexion at initial contact and throughout the absorption phase. A goal of any prevention program is to alter dynamic loading through neuromuscular training. Prevention programs enhance neuromuscular alterations by improving balance, strength, and neuromuscular coordination to facilitate joint stabilization.

The effectiveness of neuromuscular prevention programs is difficult to measure. Even in athletes performing these prevention programs, fatigue occurs and detrimental neuromuscular alterations may develop. Significant undesirable neuromuscular alterations occur with fatigue and are most applicable to what occurs during real-time athletic participation. Neuromuscular training during different magnitudes of fatigue should be considered to train the correct responses for functional movement in sports-specific athletic tasks.

Conclusion

A single session of repeated WATs induced fatigue, causing an initial reduction in peak F2 followed by an increase in peak F2. This research design offered a novel way to induce fatigue to investigate the effects of fatigue on landing kinetics. This study demonstrated a significant difference in peak GRF between nonfatigued and fatigued conditions. Increases in peak force predispose participants to lower extremity injury. Injuries associated with increased peak force and landing alterations include stress fractures and knee injuries, specifically to the ACL.

References


