Clinical Sports Medicine Update

Effect of Fatigue Protocols on Lower Limb Neuromuscular Function and Implications for Anterior Cruciate Ligament Injury Prevention Training

A Systematic Review

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Background: Approximately two-thirds of anterior cruciate ligament (ACL) tears are sustained during noncontact situations when an athlete is cutting, pivoting, decelerating, or landing from a jump. Some investigators have postulated that fatigue may result in deleterious alterations in lower limb biomechanics during these activities that could increase the risk of noncontact ACL injuries. However, prior studies have noted a wide variation in fatigue protocols, athletic tasks studied, and effects of fatigue on lower limb kinetics and kinematics.

Purpose: First, to determine if fatigue uniformly alters lower limb biomechanics during athletic tasks that are associated with noncontact ACL injuries. Second, to determine if changes should be made in ACL injury prevention training programs to alter the deleterious effects of fatigue on lower limb kinetics and kinematics.

Study Design: Systematic review; Level of evidence, 4.

Methods: A systematic review of the literature using MEDLINE was performed. Key terms were fatigue, neuromuscular, exercise, hop test, and single-legged function tests. Inclusion criteria were original research studies involving healthy participants, use of a fatigue protocol, study of at least 1 lower limb task that involved landing from a hop or jump or cutting, and analysis of at least 1 biomechanical variable.

Results: Thirty-seven studies involving 806 athletes (485 female, 321 male; mean age, 22.7 years) met the inclusion criteria. General fatigue protocols were used in 20 investigations, peripheral protocols were used in 17 studies, and 21 different athletic tasks were studied (13 single-legged, 8 double-legged). There was no consistency among investigations regarding the effects of fatigue on hip, knee, or ankle joint angles and moments or surface electromyography muscle activation patterns. The fatigue protocols typically did not produce statistically significant changes in ground-reaction forces.

Conclusion: Published fatigue protocols did not uniformly produce alterations in lower limb neuromuscular factors that heighten the risk of noncontact ACL injuries. Therefore, justification does not currently exist for major changes in ACL injury prevention training programs to account for potential fatigue effects. However, the effect of fatigue related to ACL injuries is worthy of further investigation, including the refinement of protocols and methods of analysis.

Keywords: neuromuscular; fatigue; anterior cruciate ligament

Anterior cruciate ligament (ACL) tears commonly occur in athletes $\leq$25 years of age.[63] At least two-thirds of ACL tears are sustained during noncontact circumstances when an athlete is cutting, pivoting, accelerating, decelerating, or landing from a jump.[6,7,47] Some investigations have postulated that fatigue may increase the risk of ACL injuries[5,8,27] in part because of deleterious alterations that may occur in knee and hip flexion-extension, abduction-adduction, and internal-external rotation angles and moments; ground-reaction forces (GRFs) on landing; and muscular activation patterns in the lower extremity.[14,46,51]

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Muscle fatigue is typically defined as any exercise-induced reduction in the ability of a muscle to produce force or power.[19] The decline in force or power may be attributed to central factors (brain and/or spinal cord) or peripheral factors (muscle or peripheral nervous system) and is highly dependent on the capacity of the aerobic metabolic system.[58] Central factors include altered motor neuron firing rates, decreased neurotransmitter activity, altered excitability at the cortex, and inhibition of spinal excitability by afferent feedback.[21] Peripheral fatigue may arise as a result of impaired excitation-contraction coupling through changes in action potential propagation or calcium release or impairment of enzyme activity through local acidosis.[56] In general, fatigue affects dynamic muscle control, lower limb movement patterns, and neuromuscular control and may be quantified in multiple ways.[10] The basic hypothesis for these deleterious effects is that fatigued muscles absorb less energy before reaching the degree of stretch that causes ruptures to structures such as ligaments. The multifactorial causes of fatigue have been discussed in detail elsewhere.[2,10,58]

Negative effects of fatigue on lower limb biomechanics have led investigators to recommend that fatigue resistance training be incorporated into ACL injury prevention programs.[51] However, previous reviews have found a wide variation in fatigue protocols, athletic tasks studied, and subsequent findings of investigations.[1,46] Fatigue protocols are generally categorized as either peripheral (muscle-specific) that are short in duration or general (that affect the cardiovascular and motor systems) that are long in duration. Peripheral fatigue leads to a reduction in the force-generating capacity of the muscle at or distal to the level of the neuromuscular junction.[34] It is caused mainly by metabolic factors or muscle damage if eccentric contractions are prominent and does not encompass changes in overall neuromuscular control. General fatigue protocols use gradual bouts of submaximal activity to cause a reduction in the level of voluntary muscle activation. Impairment occurs at sites proximal to the neuromuscular junction (spinal and supraspinal levels) that promote inadequate drive to the working muscles.[34] General fatigue protocols attempt to simulate realistic game or match situations[8] because it is known that fatigue effects occur cumulatively throughout a practice or game and also throughout entire athletic seasons.[33]

A wide variety of tasks have been studied in neuromuscular fatigue studies, including single-legged hopping, landing, cutting, and double-legged vertical jumping and landing. Santamaria and Webster[46] systematically reviewed fatigue effects on single-legged landing in 8 studies published from 2003 to 2008. The conclusion was that, although fatigue appeared to affect some biomechanical variables, inconsistent findings precluded definitive clinical recommendations. Factors that are believed to heighten the risk of noncontact ACL injuries include decreased hip flexion angles, increased hip internal rotation, increased hip adduction, reduced knee flexion angles, increased knee abduction angles, and increased external or internal tibial rotation. Greater external abduction and flexion moments are also believed to contribute to an increased risk, especially when accompanied by large quadriceps forces and reduced hamstring muscle activity.

The purpose of this systematic review was to determine if fatigue protocols uniformly alter lower limb biomechanics during athletic tasks that are often associated with noncontact ACL injuries. The goal was to determine if alterations should be made in ACL injury prevention training programs to reduce the deleterious effects of fatigue on lower limb kinetics and kinematics.

METHODS

Research Framework

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were used during the search and reporting phase of this review.[29]

Eligibility Criteria

Eligible articles were original studies published in English from a peer-reviewed journal that contained all of the following criteria: (1) normal, healthy participants; (2) either a peripheral or general fatigue protocol; (3) at least 1 lower limb biomechanical variable; (4) the effect of fatigue studied during 1 testing session immediately after completion of the protocol; and (5) at least 1 lower limb athletic task that involved landing from a hop or jump or cutting. Non-English, non–peer-reviewed articles, abstracts, and general review articles were excluded. Articles that assessed the effects of fatigue over time were also excluded.

Information Sources, Search, and Study Selection

A systematic review of the literature using MEDLINE from January 1, 2000 to June 1, 2016 was performed. The reference lists of all selected articles were checked by 1 author (S.B.W.) to retrieve relevant articles that may have been missed during the search. In addition, reference lists of review articles were also searched. The following key terms were used: fatigue, neuromuscular, exercise, hop test, and single-legged function tests. No limit was set other than English language and the dates of publication. The titles and abstracts were screened by 1 author. Full-text articles were read if eligibility could not be established based on the information in the abstracts.

Data Extraction and Synthesis

The extracted data included sex, age, fatigue protocol details, athletic tasks, measures of fatigue, and all prefatigue and postfatigue data reported. The findings were reviewed by both authors and agreement reached regarding the data extracted. A meta-analysis of the data was not performed because the included studies were heterogeneous with regard to fatigue protocols, athletic tasks, methods of data collection, and biomechanical factors reported.

Risk of Bias

Because of the heterogeneity of the studies, the Methodological Index for Non-Randomized Studies (MINORS) instrument was used to rate the methodological quality of the investigations.[50] The MINORS score is reported as a percentage of the total available points as recommended by Wylie et al.[60]

RESULTS

Study Selection and Study Bias

The systematic review produced 806 potential articles, 769 of which were excluded (Appendix Table A1, available in the online version of this article). The mean MINORS score of the 37 studies included in this study was 83% (range, 67%-92%).[§]

Study Characteristics

There were 806 athletes in the 37 studies, including 485 female and 321 male participants, whose mean age was 22.7 years (mean age, 21.7 years [female] and 24.3 years [male]). Details of the study designs are shown in Appendix Table A2. There were 6 studies from one research group[8,33,34,51-53] and 6 studies from another group[14-17,31,43]; the remaining 25 studies were conducted elsewhere.

Fatigue Protocols

General fatigue protocols were used in 20 studies and peripheral protocols in 17 studies (Appendix Table A3). Peripheral protocols targeted either specific muscles or the entire lower extremity. The general fatigue protocols consisted of (1) a series of different tasks (such as vertical jumps, squats, agility drills, drop-jumps) either performed until exhaustion or for a specified time period, (2) a running endurance test to exhaustion, (3) an endurance test over a specified time, or (4) a 45-minute soccer match. Indicators of fatigue such as the heart rate or perceived exertion scales were used in 16 studies.

Lower Limb Athletic Tasks

There were 21 different lower limb athletic tasks included in the 37 studies; 13 of these were single-legged activities, and 8 were double-legged activities (Appendix Table A4). The majority of investigations (n = 33) studied just 1 task. A planned (or anticipated) athletic task model was used in 28 studies, a reactive (or unanticipated) task model was used in 7 studies, and both planned and reactive task models were used in 2 studies. Planned athletic tasks involved no decision making on the part of the participant and most commonly involved a drop-jump or single-legged hop. Reactive tasks were typically used in studies that involved cutting. For instance, Borotikar et al[8] used a random light stimulus that was automatically triggered with a light beam that came up approximately 350 milliseconds before ground contact. The display directed the participant to move in the desired lateral direction upon landing from a forward jump.

Study Outcome Measures

Twenty-nine studies conducted 3-dimensional motion analyses of the athletic tasks with multicamera and force plate systems (Appendix Table A5). Kinematic and/or kinetic variables were measured at the hip, knee, and ankle in 12 studies; at the hip and knee in 14 studies; at the knee and ankle in 3 studies; and at the knee only in 6 studies. A comparison of outcome measures between male and female athletes was conducted in 11 investigations. Eight investigations provided effect sizes in addition to P values.[16,18,31,39,41-43,53] Effect sizes were interpreted according to Cohen's[13] standards in which small effects were defined as ≤ 0.2, moderate effects as 0.5, and large effects as ≥ 0.8.

Lower Limb Biomechanics

There was no consistency among investigations regarding the effects of fatigue on knee or hip joint angles (Figures 1 and 2) and moments (Figures 3 and 4). For these analyses, all athletic tasks in each study were included as well as tasks for study subgroups (such as sex or different fatigue protocols). There were no consistent differences between the peripheral and general fatigue protocols regarding the postfatigue effect on any knee or hip kinetic or kinematic variable (Table 1). There were also no consistent differences between single-legged and double-legged tasks (Table 2) regarding the postfatigue effect for any knee kinetic or kinematic variable. Of the 26 studies that measured hip angles and/or moments, only 4 used single-legged tasks, and therefore, a comparison between single-legged and double-legged tasks for hip indices was not conducted.

There were no uniform differences between planned and reactive athletic tasks regarding postfatigue effects on lower limb kinetic and kinematic variables (Table 3). The only exception was found for knee flexion, which was significantly decreased in 7 of 8 reactive tasks. In comparison, no consistency was found after fatigue for changes in knee flexion when planned athletic task models were used for analysis.

Nineteen studies reported the effects of fatigue on GRF. Only 2 studies[9,41] found significant increases in landing forces; however, one[41] of these reported a small effect size (0.14), while the other reported a mean increase from 2202.5 ± 536.29 N to 2537.86 ± 469.66 N (P = .002).[9] Several other investigations reported measuring GRFs; however, data were not presented for analysis.[‖]

Nine studies reported no significant changes in ankle dorsiflexion after fatigue,[¶] 2 reported increases in dorsiflexion,[27,32] 1 reported a decrease in dorsiflexion,[16] and 1 reported an increase in plantar flexion.[9] Four studies reported no changes in inversion-eversion angles after fatigue protocols.[18,33,45,53]

[§] References 3, 5, 8, 9, 11, 12, 14-18, 22-24, 26, 28, 30-35, 38-45, 51-53, 57, 59, 61, 64.

[‖] References 8, 12, 14, 15, 23, 33, 40, 45, 51-53, 57.

[¶] References 3, 8, 18, 33, 38, 45, 53, 57, 59.

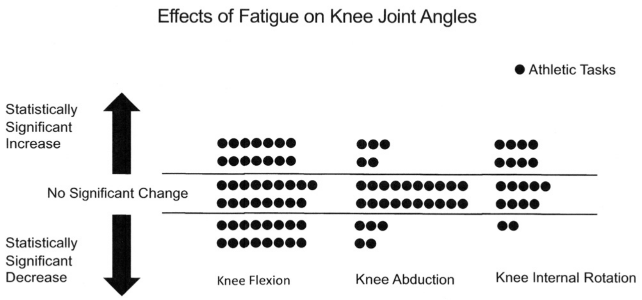

Figure 1. There were no uniform effects of fatigue on knee joint angles. Each dot indicates the result for athletic tasks for either the entire cohort or for each subgroup when comparisons were performed (such as sex, fatigue protocol, or different tasks) within a study. Knee flexion, 47 task analyses in 28 studies; knee abduction, 30 task analyses in 23 studies; and knee internal rotation, 19 task analyses in 12 studies.

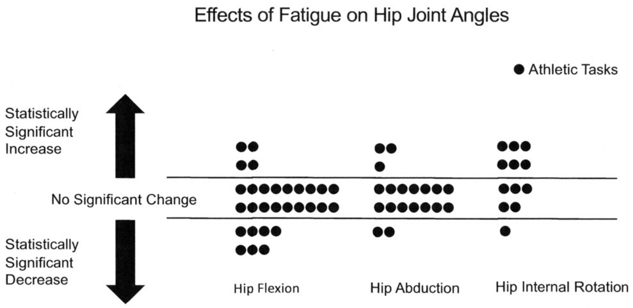

Figure 2. There were no uniform effects of fatigue on hip joint angles. Each dot indicates the result for athletic tasks for either the entire cohort or for each subgroup when comparisons were performed (such as sex, fatigue protocol, or different tasks) within a study. Hip flexion, 29 task analyses in 25 studies; hip abduction, 19 task analyses in 15 studies; and hip internal rotation, 12 task analyses in 11 studies.

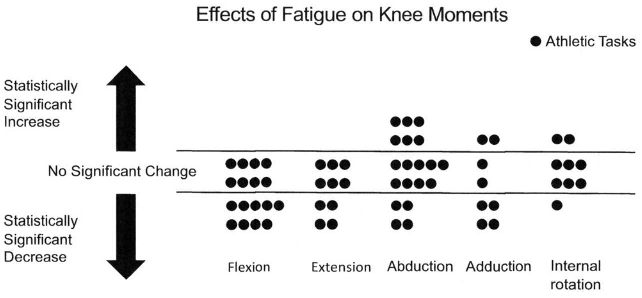

Figure 3. There were no uniform effects of fatigue on knee moments. Each dot indicates the result for athletic tasks for either the entire cohort or for each subgroup when comparisons were performed (such as sex, fatigue protocol, or different tasks) within a study. Flexion, 17 task analyses in 11 studies; extension, 10 task analyses in 7 studies; abduction, 19 task analyses in 11 studies; adduction, 8 task analyses in 7 studies; and internal rotation, 9 task analyses in 6 studies.

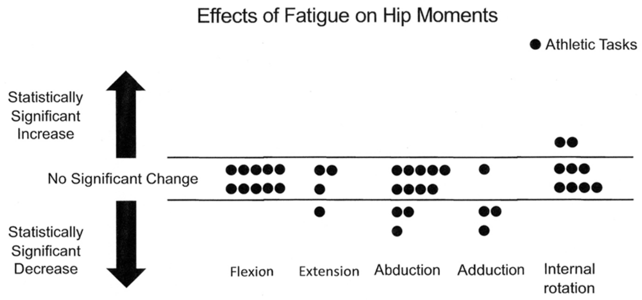

Figure 4. There were few effects of fatigue on hip moments. Each dot indicates the result for athletic tasks for either the entire cohort or for each subgroup when comparisons were performed (such as sex, fatigue protocol, or different tasks) within a study. Flexion, 10 task analyses in 9 studies; extension, 4 task analyses in 4 studies; abduction, 12 task analyses in 6 studies; adduction, 4 task analyses in 4 studies; and internal rotation, 9 task analyses in 6 studies.

Muscle Activation

There was no consistency regarding the effects of fatigue protocols on surface electromyography muscle activation patterns (Figure 5). Six studies used a single-legged task; 4 of these studied quadriceps and hamstring activity.[26,38,39,64] Two reported no changes in quadriceps activity,[39,64] 1 study reported an increase after a hamstring fatigue protocol (but no change after a quadriceps fatigue protocol),[26] and 1 reported an increase after a quadriceps fatigue protocol.[38] Four studies[22,24,40,41] used a double-legged task, one of which only reported gluteus maximus activity.[24] Two of these reported no change in quadriceps activity,[22,40] while 1 reported increased activity.[41] For the hamstrings, decreased activity was reported in 2 investigations,[22,40] while no change was found in another.[41] Gastrocnemius-soleus activity was reported in a total of 6 studies,[22,26,38,40,41,64] 3 of which found no change.[38,41,64]

DISCUSSION

The major finding of this investigation was that published fatigue protocols did not uniformly produce alterations in lower limb biomechanical factors that are believed to heighten the risk of noncontact ACL injuries. There were no consistent data that demonstrated that the type of fatigue protocol (peripheral vs general), athletic task (single-legged vs double-legged), or task model (planned vs reactive) strongly influenced changes in knee and hip kinematics and kinetics. Therefore, justification does not appear to currently exist for major changes in ACL injury prevention training programs to account for potential fatigue effects.

Because the 37 studies in our investigation were heterogeneous with regard to fatigue protocols used, athletic tasks selected, data collection methods, and biomechanical factors reported, a meta-analysis of the data could not be performed. Some studies did not include a direct measure

TABLE 1
Effect of Type of Fatigue Protocol on Changes in Lower Limb Biomechanics[a]

	Statistically Significant Effects After Fatigue		
	No Change	Increased	Decreased
Knee angles			
Flexion			
Peripheral	7	13	5
General	10	1	11
Abduction			
Peripheral	13	3	2
General	7	4	3
Internal rotation			
Peripheral	7	2	0
General	2	8	0
Knee moments			
Flexion			
Peripheral	6	0	4
General	4	0	3
Extension			
Peripheral	2	0	3
General	2	0	1
Abduction			
Peripheral	6	2	3
General	3	4	1
Adduction			
Peripheral	0	2	1
General	2	0	3
Internal rotation			
Peripheral	5	0	0
General	3	2	0
Hip angles			
Flexion			
Peripheral	12	4	2
General	9	0	5
Abduction			
Peripheral	8	3	0
General	7	0	2
Internal rotation			
Peripheral	2	4	0
General	5	2	1
Hip moments			
Flexion			
Peripheral	6	0	0
General	6	0	0
Extension			
Peripheral	4	0	1
General	0	0	0
Abduction			
Peripheral	6	0	2
General	1	0	1
Adduction			
Peripheral	0	0	2
General	3	0	1
Internal rotation			
Peripheral	4	1	0
General	4	1	0
Landing forces[b]			
Peripheral	7	0	5
General	7	2	1

[a] Values represent number of athletic tasks.

[b] One single-legged landing task study reported a decrease in landing forces after a quadriceps fatigue protocol but no change after a hamstring fatigue protocol. Another single-legged landing task study reported no change in landing forces after either a general or peripheral fatigue protocol.

TABLE 2
Effect of Type of Athletic Task on Changes in Lower Limb Biomechanics[a]

	Statistically Significant Effects After Fatigue		
	No Change	Increased	Decreased
Knee angles			
Flexion			
Single-legged	11	11	9
Double-legged	6	3	6
Abduction			
Single-legged	16	2	4
Double-legged	4	3	1
Internal rotation			
Single-legged	7	4	2
Double-legged	2	4	0
Knee moments			
Flexion			
Single-legged	4	0	9
Double-legged	4	0	0
Extension			
Single-legged	3	0	4
Double-legged	3	0	0
Abduction			
Single-legged	7	3	4
Double-legged	2	3	0
Adduction			
Single-legged	2	2	3
Double-legged	0	0	1
Internal rotation			
Single-legged	6	0	1
Double-legged	9	2	0
Landing forces			
Single-legged	10	1	2
Double-legged	3	1	1

[a] Values represent number of athletic tasks.

of muscular fatigue (such as loss of muscle power) to indicate when the protocol should end and thus appeared to assume that a fatigued state had been reached by all participants.[16,33,41,45,61,64] These investigations used protocols that were either based on a set amount of repetitions or time in which certain athletic tasks (such as vertical jumps, squats, agility drills, drop-jumps) were performed. Using time alone as an indicator of fatigue is problematic because athletes have inherent sets of parameters that involve complex central and metabolic factors. The lack of attention to potential between-participant variations in cardiovascular and muscular endurance may confound biomechanical findings. In addition, studies have shown that women exhibit different fatigue levels and characteristics than men and that the magnitude of sex differences is specific to the task performed and the muscle groups involved.[25]

The effects of fatigue on cutting tasks were studied in 11 investigations. Examples of the variations in findings regarding changes in knee flexion, abduction, and internal rotation angles after fatigue are shown in Table 4. Four studies that used general fatigue protocols and a planned athletic task model found no significant change in knee flexion.[8,14,45,64] However, 4 studies reported significant decreases in knee flexion that ranged from 3° to 10°, and

TABLE 3
Effect of Type of Task Model
on Changes in Lower Limb Biomechanics[a]

	Statistically Significant Effects After Fatigue		
	No Change	Increased	Decreased
Knee angles			
Flexion			
Planned	18	14	10
Reactive	1	0	7
Abduction			
Planned	21	7	22
Reactive	1	2	3
Internal rotation			
Planned	8	5	0
Reactive	2	4	0
Knee moments			
Flexion			
Planned	6	0	7
Reactive	2	0	3
Extension			
Planned	4	0	3
Reactive	0	0	1
Abduction			
Planned	3	4	2
Reactive	2	1	2
Adduction			
Planned	1	2	3
Reactive	1	0	1
Internal rotation			
Planned	9	2	0
Reactive	1	0	0
Hip angles			
Flexion			
Planned	22	4	3
Reactive	2	0	5
Abduction			
Planned	15	3	0
Reactive	3	0	2
Internal rotation			
Planned	7	9	0
Reactive	0	2	1
Hip moments			
Flexion			
Planned	13	0	0
Reactive	3	0	0
Extension			
Planned	4	0	0
Reactive	0	0	1
Abduction			
Planned	6	0	2
Reactive	1	0	1
Adduction			
Planned	2	0	5
Reactive	1	0	1
Internal rotation			
Planned	7	5	0
Reactive	0	1	0
Landing forces			
Planned	10	2	6
Reactive	4	0	1

[a] Values represent number of athletic tasks.

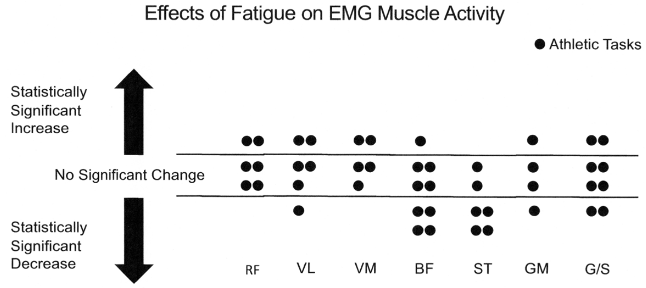

Figure 5. There were no uniform effects of fatigue on electromyography muscle activation patterns. Each dot indicates the result for athletic tasks for either the entire cohort or for each subgroup when comparisons were performed (such as sex, fatigue protocol, or different tasks) within a study. RF, 6 task analyses in 6 studies; VL, 6 task analyses in 5 studies; VM, 5 task analyses in 5 studies; BF, 9 task analyses in 7 studies; ST, 6 task analyses in 5 studies; GM, 4 task analyses in 4 studies; and G/S, 8 task analyses in 6 studies. BF, biceps femoris; GM, gluteus medius; G/S, gastrocnemius-soleus; RF, rectus femoris; ST, semitendinosus; VL, vastus lateralis; VM, vastus medialis.

the majority of these used a reactive task model.[14,15,31,34] There was no significant change in landing forces in the 3 studies that provided these data.[31,34,64] Regarding alterations in hip angles, only 3 studies reported decreased hip flexion (range, 3.6°-8.4°) after fatigue, all of which used general fatigue protocols and reactive athletic tasks.[8,15,31] Six other studies found no significant change in hip flexion after fatigue.[14,23,34,45,53,64] Four studies reported increases in hip internal rotation that ranged from 0.8° to 6.9° after both planned and reactive athletic tasks and either a general or peripheral fatigue protocol.[8,31,34,53] Only 3 studies reported hip abduction angle results, which was increased in 2 studies[15,23] and not significantly changed in 1 study.[14]

The effects of fatigue on drop-jump tasks (double-legged and single-legged) were analyzed in 14 investigations. Effects on knee angles were analyzed in all of these studies, but the effects on hip angles were only assessed in 8 studies. Peripheral fatigue protocols were used in 8 studies, and all but 2[11,42] of these reported significant increases in knee flexion after fatigue (range, 2.4°-10.7°).[18,22,26,27,30,32] General fatigue protocols were used in 6 studies, of which only 1 reported a significant increase in knee flexion (6.5°),[9] while the others found no significant changes. Only 2 studies reported increases in knee abduction angles that ranged from <2°[11] to 6.8°,[33] and only 2 reported increases in knee internal rotation angles that ranged from 3.6°[57] to 7.2°.[33] The remaining investigations either found no increases or did not study these factors. Five studies[30,32,33,42,57] reported no changes in hip flexion, and 3 reported increases that ranged from 3.4° to 8.9°.[18,26,27] Significant decreases in landing forces were noted in 4 studies,[18,22,26,32] increases were found in 2 studies,[9,41] and no change was reported in 3 studies.[11,27,42]

TABLE 4
Change in Knee Flexion, Abduction, and Internal Rotation Angles After Fatigue in Cutting Task Studies[a]

	Fatigue Protocol		Knee Flexion, deg		Knee Abduction, deg		Knee Internal Rotation, deg		Landing Forces	
Study	General/ Peripheral	Planned/ Reactive	Change After Fatigue[b]	P Value/ ES	Change After Fatigue[b]	P Value/ ES	Change After Fatigue[b]	P Value/ ES	Change After Fatigue[b]	P Value/ ES
Thomas et al[53] (2011)	Peripheral: hip rotators	Planned	↓ 1.6	.01/0.34	NS		NS		NA	
	Peripheral: triceps surae	Planned	↓ 2.0	.01/0.36	NS		NS			
Geiser et al[23] (2010)	Peripheral: hip abductors	Planned	NS		NA		NA		NA	
Sanna and O'Connor[45] (2008)	General	Planned	NS		NA		↑ 3.3	.01/NA	NA	
Zebis et al[64] (2011)	General	Planned	NS		NA		NA		NS	
Borotikar et al[8] (2008)	General	Planned	NS		↑ 0.8	<.001/NA	↑ 1.3	<.001/NA	NA	
		Reactive	NS		↑ 3.6	<.001/NA	↑ 3.8	<.001/NA		
McLean and Samorezov[34] (2009)	General	Planned	↓ 6.0	<.01/NA	↑ 0.6	<.01/NA	NS		NS	
		Reactive	↓ 4.8	<.01/NA	↑ 3.8	<.01/NA	NS			
Cortes et al[14] (2014)	General	Planned	NS	<.001/NA	NA		NA		NA	
	General	Reactive	↓ 10.0		NA					
Cortes et al[15] (2013)	General	Reactive	↓ 3.0	.004/NA	↑ 1.1	.03/NA	NA		NA	
Lucci et al[31] (2011)	General, fast	Reactive	↓ 3.2	.02/0.38	NS		↑ 1.3	.04/0.45	NS	
	General, slow	Reactive	↓ 3.2		NS		↑ 3.7	.04/0.45		

[a] ES, effect size; NA, not available; NS, not statistically significant.
[b] Changes were calculated from prefatigue and postfatigue mean values provided in these studies.

Single-legged hop tests are frequently used clinical measures to detect overall lower limb asymmetry. Five studies ascertained the effect of fatigue on hop tests; 2 used general fatigue protocols,[44,61] and 3 used peripheral protocols.[3,38,52] Neither general fatigue model resulted in significant decreases in hop distance immediately after the conclusion of the protocol. For instance, Ros et al[44] reported that, although the mean heart rate was 180 beats per minute in 10 women after an intermittent endurance test, the hop distance only decreased a mean of 2 cm. Peripheral fatigue protocols had varying results related to lower limb biomechanics. One study reported a mean increase in hip internal rotation of 3.3° at initial contact from a single-legged hop but no significant differences in hip extension or abduction.[52] In this study, knee external rotation increased a mean of 2.7°, and knee extension increased a mean of 5.4°. Another investigation reported a significant increase in mean knee flexion of 14° and a significant decrease in hip flexion of 5.6° on landing from a single-legged hop.[38]

One problem highlighted in this review is that only 8 studies (22%) provided effect sizes in addition to *P* values. The effect size measures the magnitude of the effects of treatment and is especially relevant in studies with small sample sizes.[20] It is probable that some statistically significant findings ($P < .05$) may have limited clinical relevance. For instance, 1 study reported a mean increase in knee flexion after a peripheral (quadriceps muscle) fatigue protocol of 4.8° ($P < .05$) on landing from a double-legged hop in 10 women.[40] The clinical relevance as related to an increase in the risk of sustaining a noncontact ACL injury because of small changes in knee flexion is questionable. Only 1 study reported a large effect size on a drop-jump task (eg, increased knee flexion of 5.8° and effect size of 2.32 and increased hip flexion of 3.4° and effect size of 1.49).[18]

Another problem detected in this review was the sample size selected in many studies. Only 20 studies (54%) conducted a prospective power calculation of the size required to discern a detectable difference (95% CI), although several did not provide the expected (or hypothesized) mean ± SD of relevant variables required to achieve a sufficient sample size.[23,27,30,41,57] Patrek et al[42] selected a change of greater than 3° of hip or knee frontal-plane flexion and abduction in their sample size determination, based on data from a prior study that showed that this magnitude represented a moderate to large effect size (0.7). Sanna and O'Connor[45] selected a 2° difference in frontal-plane hip and knee kinematics, based on pilot data, to determine their sample size. Ros et al[44] used a performance indicator of a difference of 10 cm in a single-hop distance (from baseline to after fatigue) as clinically relevant to determine the cohort size. The determination of which variables are the most relevant to the noncontact ACL injury dilemma, and the magnitude of change in these variables that represents a true risk indicator (eg, 10° of decreased knee flexion), requires clarification in future studies.

A third problem is that the majority of studies reported means ± SDs only; ranges were frequently not provided, nor were the percentages of participants whose postfatigue results placed them in a (hypothesized) heightened risk category for a noncontact ACL injury. Reporting the percentage of participants who had significant or clinically relevant changes for each biomechanical factor analyzed is recommended. In addition, the development of a biomechanical profile for each athlete would also be helpful in future studies. The use of tests such as the drop-jump, knee arthrometer testing, and isokinetic strength allows the identification of patients who may have a higher risk profile for ACL injuries.[4,36,37,49,54] Then, the effects of either general or peripheral fatigue protocols, reactive or planned athletic tasks, and various athletic tasks (cutting, landing, etc) could be analyzed according to the biomechanical profile. Another statistical method to consider is equivalence testing, whereby specification is made of the amount (range) of difference between prefatigue and postfatigue variables that is considered equivalent.[55] When proven, the results indicate that the 2 test conditions (prefatigue and postfatigue) are close enough so that one cannot be considered superior or inferior to the other.

McLean et al[33] previously recommended the development of standardized tasks to determine local and central fatigue effects. It would be advantageous for future studies to uniformly incorporate specific fatigue indicators, such as direct measurements of the heart rate and muscular power. Consensus needs to be reached of these measures in terms of when fatigue has been reached, such as the percentage of maximum vertical jump height or peak isokinetic torque compared with baseline values. For instance, the studies in this review that used vertical jump height selected ranges from 10% of baseline[15,30] to 20% of baseline[57] to indicate that fatigue had been achieved without providing a rationale for these values.

CONCLUSION

The hypothesized factors that heighten the risk of a noncontact ACL injury include decreased hip and knee flexion angles, increased hip internal rotation, increased hip adduction angles, increased knee abduction angles, increased external or internal tibial rotation, increased external abduction and flexion moments, increased quadriceps forces, and reduced hamstring activity.[48,62] The major finding of this study was that published fatigue protocols did not uniformly produce alterations in these lower limb biomechanical factors. The large variation in findings indicates the need for continued research in this area and the refinement of fatigue protocols, athletic tasks selected for analysis, and methods of analysis. Improved future studies may then better determine if changes are required in ACL neuromuscular prevention training programs to account for fatigue effects.

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