THE EFFECT OF FATIGUE PROTOCOLS ON KNEE CONTROL DURING FUNCTIONAL ACTIVITIES: A SYSTEMATIC REVIEW

This thesis is presented in partial fulfilment of the requirements for the degree of Master of Science in Physiotherapy at Stellenbosch University

Jaco Pretorius

Supervisors: Prof. Quinette Louw, PhD (Stellenbosch University)

Dr. Linzette Morris, PhD (Stellenbosch University)

November 2014

Declaration Page

I, the undersigned, hereby declare that the work contained in this thesis is my original work and that I have not previously submitted it, in its entirety or in part, at any university for a degree.

Signature:  **Date:** November 2014

Abstract

Introduction

ACL injuries are among the most serious injuries that professional and amateur sports men and women sustain. More than 120 000 ACL injuries occur annually in the USA alone. The highest incidence of ACL injuries are seen in multi-directional and multi-factorial sports such as soccer, basketball, lacrosse, American football, rugby and Australian rules football. It is hoped that the proposed review will clarify issues relating to the effect of fatigue on knee control, as it will focus on multiple movements found in different sporting codes. By including both studies on healthy adults as well as subjects who have sustained ACL injuries, a clearer picture can be formed on the global effect of fatigue on knee control.

Objective

The objective of this review was to identify, collate and analyse the current evidence on the effect of fatigue protocols on knee control during functional tasks, such as side-stepping, bilateral jumping/landing and crossover-cutting.

Methodology

A comprehensive search of electronic databases was conducted between April 2013 and August 2013 (updated in April 2014) for eligible articles for inclusion in the review. Methodological quality was assessed using a modified Downs and Black checklist.

Results

Ten studies met the eligibility criteria and were included in the review. The included studies reported a wide variety of fatigue protocols. Several different test movements were utilised in the studies. The test movements included cutting movements, drop jumps, stop jumps, vertical jumps, bilateral drop landing and rotational movements. The overall results indicated that fatigue had a negative impact on knee control. There were however studies which reported conflicting results. Gender differences were also highlighted in the results of included studies where it became evident that females tend to be more susceptible to knee injuries due to altered kinematics as a result of fatigue.

Conclusion

Fatigue generally seems to affect knee control negatively across various fatigue protocols. Future research should investigate using a standardised fatigue protocol to achieve more accurate and consistent results during the different functional activities.

Acknowledgement

I would like to sincerely give my thanks to:

- God, my Heavenly Father, for giving me the strength and ability to complete this project.
- Professor Quinette Louw and Doctor Linzette Morris for their support, advice, corrections and guidance provided throughout the entire study process.
- My wife and three wonderful children for their endless love and support.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ACL	Anterior Cruciate Ligament
ROM	Range Of Motion
SD	Standard Deviation
3D	Three Dimensional
2D	Two Dimensional
EMG	Electromyography
ACLR	Anterior Cruciate Ligament Reconstruction
VAS	Visual Analogue Scale
IKDC	International Knee Documentation Committee
MeSH	Medical Subject Headings
JBI	Joanna Briggs Institute
HREC	Health Research Ethics Committee
NBA	National Basketball Association
NFL	National Football League

List of Definitions

Biomechanics	The science concerned with the internal and external forces acting on the human body and the effects produced by these forces. (www.starter-project.com/Presentazioni/Cappello.pdf)
Kinetics	Examines the forces causing a movement (www.starter-project.com/Presentazioni/Cappello.pdf)
Kinematics	Spatial and temporal components of motion (position, velocity, acceleration) with no consideration of the forces causing the motion (www.starter-project.com/Presentazioni/Cappello.pdf)
Knee Varus/Adduction	The tibia is angled inward in relation to the femur, resulting in adduction of the knee (Kamath et al, 2010).
Knee Valgus/Abduction	The tibia is angled outward in relation to the femur, resulting in abduction of the knee (Kamath et al, 2010).
Contralateral	Taking place or originating in a corresponding part on the opposite side as pain (www.medterms.com).
Bilateral	Affecting both sides (www.medterms.com).

Proprioception	The ability to sense stimuli arising within the body regarding position, motion, and equilibrium. (www.medterms.com).
Isokinetic	Maintaining constant torque or tension as muscles shorten or lengthen. (www.medical-dictionary.thefreedictionary.com)
Agonist	A substance that acts like another substance and therefore stimulates an action. (www.medterms.com).
Antagonist	A substance that acts against and blocks an action. (www.medterms.com).
PEARLing	PEARL Growing or PEARLing is the process of using one information item (like a subject term or a reference list) to find more information. (http://en.wikipedia.org/wiki/Pearl_growing)
Fatigue	The extreme tiredness resulting from mental or physical exertion or illness; a reduction in the efficiency of a muscle or organ after prolonged activity. (www.oxforddictionaries.com/definition/english/fatigue)

Chapter 1: Introduction

The epidemiology of ACL injuries

Anterior cruciate ligament (ACL) injuries are among the most serious injuries that sportsmen or -women are faced with.[1] Alentorn-Geli *et al*[2] reported that there are about 120 000 ACL injuries per year in the United States of America (USA) alone. In addition, Nicolini *et al*[29] found that soccer injuries were the most reported in the clinical setting and that 50% of the reported knee injuries were ACL injuries. These figures are alarming since ACL injuries cause significant time lost from sport and work.

The prevalence of ACL injuries are the highest in sports that require multidirectional movement along with multiple factors such as catching, kicking and avoiding contact with opponents.[7] These types of sports include, but are not limited to, soccer, basketball, volleyball, lacrosse, Australian rules football, American football and rugby.[1, 3-7] Studies suggest that the highest number of ACL injuries occur in soccer, basketball and volleyball.[38, 29, 34] Conflicting evidence does however exist. For example, Prodromos *et al*[38] concluded that volleyball might in fact be a very low risk sport for ACL injuries as no ACL ruptures were reported in this sport. Nevertheless, the highest numbers of ACL injuries occurring in multidirectional sports are non-contact injuries.[1, 3, 5, 6, 27] These injuries predominantly occur due to a combination of a sudden change in direction and deceleration of the knee joint during movements such as side-stepping and crossover cutting.[3, 5, 6, 34] In addition, landing from a jump with the knee in an extended position also increases the risk of injury.[34] Athletes who have a strength discrepancy in their quadriceps and hamstring muscles are also at a high risk of sustaining an ACL injury. The mismatch in strength predisposes the athlete to anterior tibial translation which leads to stress being placed on the ACL.[34]

ACL injuries tend to vary between gender, sport, mechanism of injury and the injury prevention programme that athletes are exposed to.[38] It has become evident through recent research that females seem to be more susceptible to ACL injury or ruptures than their male counterparts.[34] Liable *et al*[34] stated that the number of females participating in sport has risen quite significantly in recent years. The increase in participation has led to an increase in non-contact ACL injuries among female athletes.[34] The available research on the ACL injury ratio of females to males tends to differ from study to study. In a study by Prodromos *et al*[38] in 2007 the ACL tear rate in different sports were compared between females and males. It was reported that, when looking at multidirectional sports, the highest female to male injury rate was seen in basketball where females had a rate of 3.5:1. This trend continued in indoor soccer (2.77:1), soccer (2.67:1), rugby (1.94:1) and lacrosse (1.18:1). The only exception was seen in alpine skiing where the female to male rate was 1:1. Waldén *et al*[27] reported on the injury rate in 57 elite soccer clubs in the Swedish professional men's and women's leagues and men's professional leagues in Europe. As with most studies, it was found that females had a higher ACL injury rate than their male counterparts. It was also found that females tend to injure their ACL at a younger age compared to males. The mean age of ACL injury for females were 20.6 ± 2.2 years compared to 25.2 ± 4.5 years for males. Waldén *et al*[27, 35] reported in two different studies that females have a higher ACL injury rate in match conditions compared with training. In their 2011 study, Waldén *et al*[27] found a match to training rate of 20.8:1 for ACL injuries among females.

Return to sport following an ACL injury/reconstruction

ACL ruptures are responsible for some of the lengthiest lay-offs from active participation in sport. Gobbi *et al*[31] stated that ACLR is recommended in athletes following an ACL rupture as to restore normal knee function and allow patients to return to the sporting field. However, in a study by Harris *et al*[33] in 2013 it was reported that professional basketball players who underwent anterior cruciate ligament reconstruction (ACLR) surgery only returned to active participation the next season, an average of 11.6 ± 4.1 months after the initial injury.[33]

In addition, Gobbi *et al*[31] conducted a study on the factors influencing return to sport in athletes who had undergone ACLR surgery with patellar tendon or hamstring tendon graft which was published in 2006. When comparing the different grafts used Gobbi *et al*[31] reported no statistical difference between the effectiveness of using either of the grafts. It was reported in the study that successful ACLR surgery using either the patellar tendon or the hamstring tendon graft combined with a well-structured rehabilitation program, could lead to an athlete returning to the same level of function as prior to the ACL rupture.

The serious nature of ACL injuries and ruptures results in athletes not being able to take part in their chosen sport for a prolonged period. Most studies reporting on return to sport post ACLR come to fairly similar conclusions. Waldén *et al*[27] reported on the time that it took for professional soccer players to return to sport following ACLR surgery. The mean time for return to play in this study was 201.8 ± 81.7 days. Furthermore, 94% of the players who suffered an ACL rupture returned to training 10 months after the initial injury. 89% of the injured players took part in a match within 12 months of the initial ACL injury.

Erickson *et al*[32] published a study in 2014 on the performance and return to sport of NFL quarterbacks following ACLR surgery. It was reported that 92% of the subjects were able to return to sport within the NFL. The athletes who returned to the NFL played for a mean of 4.85 ± 2.7 years following their return. No significant differences were seen between the athlete's pre- and post-injury performance. Harris *et al*[33] reported on return to sport following ACLR surgery in the NBA. Contrary to Erickson *et al*[32] it was found that players did not perform at their pre-injury level at their return to full participation. Only 86% of the ACLR players returned to the NBA, whereas 12% of players returned to sport at one league lower than before. The significant result from this study is that the players only returned to full competition 11.6 ± 4.1 months following the initial injury.

Fatigue as a risk factor for injury (and re-injury) of the ACL

According to Corin *et al*[39], "Muscle fatigue is a complex and multifaceted process involving physiological, biomechanical, and psychological elements. It is an important phenomenon, as there are numerous proven relations with work related musculoskeletal injuries." Previous studies tended to assess the limit of endurance rather than fatigue as defined by Corin *et al*. Their study further highlights the knowledge gap in how muscle fatigue is assessed.[39]

Injuries to the ACL tend to occur in the latter stages of matches. In 2000, Gabbett *et al*[10] reported that most ACL injuries which were reported over three seasons in an amateur rugby league tournament occurred in the second half of matches. Similar findings were reported in a 2006 study by Junge *et al*[11]. The study found that the majority of ACL injuries reported in the soccer tournament at the 2004 Olympic

Games were sustained in the second half of matches. Similarly, a study conducted on professional basketball players in the NBA by Harris *et al*[33] in 2013 revealed that 40% of all ACL ruptures occurred in the fourth quarter of the match. Studies have also revealed that overuse injuries tend to occur to the latter end of the season.[10, 12] These results would suggest that athletes are at risk of sustaining ACL injuries in the second half of matches, regardless of whether athletes are competing in recreational or professional matches. Greig and Siegler[37] contributed this increase in risk to the increase in fatigue that the athletes were experiencing. Similar findings were seen in a 2012 study published by Changela *et al*[26] where it was reported that the subjects experienced a decline in knee proprioception which was directly attributed to the increase in the level of fatigue that subjects were experiencing. The development of effective training and rehabilitation programs to counteract the effects of fatigue and possibly reduce the risk of injury (re-injury) of the ACL during sport is therefore emphasized.[10-12, 26, 33, 37]

Purpose of review

Prior to developing ACL injury (re-injury) prevention programs, an understanding of the effect of fatigue on knee control is required. The following review therefore aims to explore the current evidence on the effect of fatigue protocols on knee control during functional tasks, such as side-stepping, bilateral jumping/landing and crossover-cutting. The results of this review may contribute to the knowledge base by providing trainers and clinicians with the necessary information to develop rehabilitation or training protocols for patients following ACL reconstruction or healthy athletes in order to prevent injury or re-injury of the ACL.

Chapter 2: Systematic Review

The Effect of Fatigue Protocols on Knee Control During Functional Activities - *A Systematic Review*

Submitted to BMC Musculoskeletal Disorders

Journal Guidelines in Appendix A

Jaco Pretorius, *MSc PT* [i], Quinette Louw, *PhD* [i,ii] (supervisor), Linzette Morris, *PhD* [i] (co-supervisor)

i. Division of Physiotherapy, Faculty of Medicine and Health Sciences, Stellenbosch University, Cape Town, South Africa

ii. FNB 3D Movement Analysis Laboratory, Faculty of Medicine and Health Sciences, Stellenbosch University, Cape Town, South Africa

INTRODUCTION

Knee control is a multi-faceted concept. It is a combination of joint kinematics linked to the neuromuscular activation of the synergist and antagonist muscle groups. These muscle groups control the acceleration and deceleration forces applied to the joint during active movement. Control is further enhanced by the neural input of the stretch receptors and Golgi tendon organs in the individual muscles, overlaid with the proprioceptive input from this specialised group of nerve receptors. Altering knee biomechanics will interfere/alter knee control as it will alter one or more of the facets which contribute to knee control/stability.[42]

ACL injuries are among the most serious injuries that professional and amateur sportsmen and -women are faced with.[1] More than 120 000 ACL injuries occur annually in the USA alone.[2] The highest incidence of ACL injuries are seen in multi-directional and multi-factorial sports such as soccer, basketball, lacrosse, American football, rugby and Australian rules football.[1, 3-7] In most of these sports, the highest number of ACL injuries occurs during non-contact injuries.[1, 3, 5, 6]

According to the American Academy of Orthopaedic Surgeons[40] and the Department of Orthopaedic Surgery at the University of California, San Francisco[41], 50% of annual ACL injuries in the USA require reconstruction. It is estimated that 20% to 25% of young active athletes will sustain a second knee injury following ACL reconstruction surgery.[2, 8] The reason for this alarmingly high rate of re-injury has not yet been fully established. In addition, some evidence suggests that at six months post-ACL reconstruction surgery, patients have a quadriceps muscle deficit exceeding 20%.[9] Less than half of athletes therefore return to the sport field within the first year following an ACL reconstruction.[2] Understanding the mechanism of injury and specific factors leading to these mostly non-contact injuries are thus crucial in preventing such injuries from occurring/re-occurring.

Evidence shows that most ACL injuries or re-injuries on the playing field occur during movements such as side-stepping, jumping, landing, sudden deceleration and crossover-cutting.[3, 5, 6] Athletes taking part in multi-directional sports are constantly exposed to these potentially damaging movements during training and match situations.[3] Side-stepping was the most common manoeuvre causing ACL injuries in a study on injuries in Australian rules football, with the most injuries occurring when side-stepping at a medium pace.[5] This could explain the possible high injury rate when athletes tire towards the latter stages of a game. Studies have shown that a large number of injuries, including ACL injuries (primary or secondary), in rugby league and soccer occur during the second half of matches.[10, 11] Furthermore, there is a higher incidence of overuse injuries in the latter stages of the season compared to the start of the season.[10, 12] In 2009, Greig and Siegler[37] published a study where they replicated the activity profile of a soccer match (intermittent treadmill protocol), including a 15 minute static halftime period. The results showed that there was a higher risk of injury (muscle and joint) in the latter stages of match play and at the start of the second half. The authors attributed the increased injury risk to the increase in fatigue of the players.

Changela et al[26] described the effect of fatigue on knee proprioception. The results of this study showed that fatigue reduced knee joint proprioception. The authors concluded that a decrease in proprioception would lead to an increased risk of injury.[14] Based on the findings of the above-mentioned studies[10-14] it can be suggested that fatigue is potentially one of the major contributing factors to the high number of ACL injuries often seen in multi-directional sports.

Santamaria and Webster[25] published a systematic review in which they only focused on single-limb landings and none of the other high risk movements. The authors recommended that future studies should focus on fatigue protocols that introduce fatigue locally and centrally. In addition, the authors suggested that further reviews should include subjects who are recovering from injury or surgery.

However, to my knowledge, no systematic review has to date collated the available evidence on the effect of fatigue protocols on knee control during functional tasks. To date there are also limited studies on the effect of fatigue on the knee control of patients with previous ACL reconstruction/repair. The few available studies are also not of a high level (1-3) of evidence. This indicates a serious knowledge gap in the literature on this specific topic. The objective of this review was thus to identify, collate and analyse the current evidence on the effect of fatigue protocols on knee control during functional tasks, such as side-stepping, bilateral jumping/landing and crossover-cutting. This study may contribute to clarifying issues relating to the effect of fatigue on knee control, as it will focus on multiple movements found in different sporting codes. By including both studies on healthy adults, as well as subjects who have sustained ACL injuries and have had subsequent surgery, a clearer picture can be formed on the global effect of fatigue on knee control in preventing injury and re-injury of the ACL. The results could lead to possible changes in rehabilitation or training protocols following ACL reconstruction or normal training methods to counter the possible effects of fatigue on knee control.

REVIEW OBJECTIVES

- The objective of this review was to identify, collate and analyse the current evidence on the effect that fatigue protocols, both general and local (to lower limb), have on knee control during functional tasks, such as bilateral lower limb landings, side stepping and jump tasks. Studies reporting on single-limb landings in participants with previous ACL reconstruction were also included as the systematic review by Santamaria and Webster[25] included only subjects who were free from prior injuries.
- Furthermore, the review aimed to critically appraise the identified studies to identify ways of improving the quality of future research.

SECONDARY REVIEW OBJECTIVES

- As a secondary objective, gender differences, will be assessed as preliminary searches revealed a possible higher incidence of knee/ACL injuries in female subjects.
- Identify possible gender differences in the effect that fatigue protocols have on knee control.
- Identify similarities and differences in fatigue protocols used in the included studies.

METHODOLOGY

Inclusion Criteria

Type of Studies

All relevant studies including controlled laboratory studies, pre-test post-test experimental design studies and repeated measures studies published between 1990 and 2014 were sought and assessed for inclusion in the review. A preliminary search revealed a lack of availability of level 1, 2 and 3 evidence studies in this particular field of study. In the absence of descriptive studies, case series and case studies were considered. No other research designs such as systematic reviews, etc. were considered. Only English studies that were available as full text articles were included.

Type of Participants

Participants were not limited to any race, nationality, gender or culture. Participants were adults between the ages of 18 and 60 years. Participants included had to fall into one of two categories. The first category was healthy participants who were free from any current or previous knee injuries. The second category was participants who had undergone previous ACL reconstruction surgery. Refer to table 1 for included participants.

Type of Intervention

Only descriptive studies reporting on introducing fatigue in participants while assessing knee control were included. Any type of (general or specific) fatigue protocol was allowed for inclusion in the review, such as repetitive squats, repetitive eccentric isokinetic exercise or cycling until participants were not able to continue the exercise.

Type of Outcome Measures

Outcomes of interest included the evaluation of knee control (e.g. knee stability and proprioception) by movement analysis. Movement analysis included the use of 2D and 3D cameras and the use of a force plate. Functional tests and isokinetic muscle analysis using EMG measuring was also included in the study.

Search Strategy

An extensive search was conducted between April 2013 and August 2013 in 15 electronic databases available on the Stellenbosch University website/library. An update of the search was conducted during April 2014. All the databases were searched for articles published between 1990 and 2014. The databases that were searched include: *PubMed, CiNAHL, Cochrane Library, BIOMED central, PEDro, Science Direct, Proquest Medical Library, BMJ.com, clinicaltrials.gov, Ingenta Connect, HireWire Press, Sport Discus, Scirus, Scopus* and *Springerlink.*

Several search strategies were used according to the databases searched. The main keywords used in the searches included: *Knee control, fatigue, healthy adults, ACL injury, ACL reconstruction*. In certain searches, MESH terms were used. These were: *knee stability, dynamic knee stability, knee biomechanics, knee proprioception, knee kinetics, knee kinematics* and *muscle fatigue.*

The reference lists of included trials were searched for additional trials (PEARLing). Hands searching of journals not indexed in electronic databases were excluded, as this method is difficult to replicate.

Selection of Studies

Two reviewers independently assessed the studies that were identified using the keyword searches. The titles and abstracts were read by the reviewers to ascertain whether they met the inclusion criteria. If studies were deemed relevant, the full text was retrieved. These were further assessed for relevance before the final selection for inclusion was made. Disagreements were solved by consensus.

Assessment of Methodological Quality

Two independent reviewers critically appraised each selected study. Disagreements were resolved through conversation until consensus was reached. If consensus could not be reached, a third persons' opinion was sought. The Downs and Black revised checklist was used to critically appraise each study. This tool is appropriate for assessing non-randomised control trials. The tool consists of 27 items of which 13 were relevant to assessing potential sources of bias in non-randomised studies.

The modified checklist requires a yes/no response, with a ‘yes’ response being allocated one point, and a ‘no/unclear’ response being allocated zero points. Thus a maximum score of 13 can be allocated if the study meets all criteria.

Data Extraction

Data was extracted using the *JBI data extraction tool*. Data collected included: *year of publication, study author, country of publication, study design; details of randomization (if used); study population; sample size, age range, gender, intervention; control, outcomes; quality and result of study analysis.* When necessary, attempts to contact the researchers of a study to obtain missing information was made.

Data analysis and synthesis

Meta-analysis was not possible due to heterogeneity in fatigue protocols, samples and outcomes. Where possible the data was presented graphically as a forest plot. All other data was narratively described using tables.

RESULTS

Search Results

A comprehensive search of 15 databases yielded 9961 hits. After reviewing titles and abstracts, 54 full text articles were reviewed. After removing articles that did not meet the inclusion criteria or were duplicates, seven articles remained. When PEARLing was applied, a further three articles were found that were relevant. Thus ten articles were deemed relevant for this review (Figure 1).

Databases	Initial Hits	Relevant Articles	Accepted Full Texts	Duplicate
Biomed central	217	4	0	
BMJ.com	57	0	0	
Cinahl	25	4	1	Y
Clinical trails.gov	17	0	0	
Cochrane library	20	2	0	
Higherwire press	344	4	2	Y
Ingenta connect	52	4	0	
Pedro	29	0	0	
Proquest medical library	1739	5	0	
Pubmed	137	12	2	Y
Science direct	1438	1	1	
Scirus	4520	0	0	
Scopus	118	6	3	Y
Sportsdiscus	37	10	2	Y
Springerlink	1211	2	0	
Total	**9961**	**54**	**11**	**5**

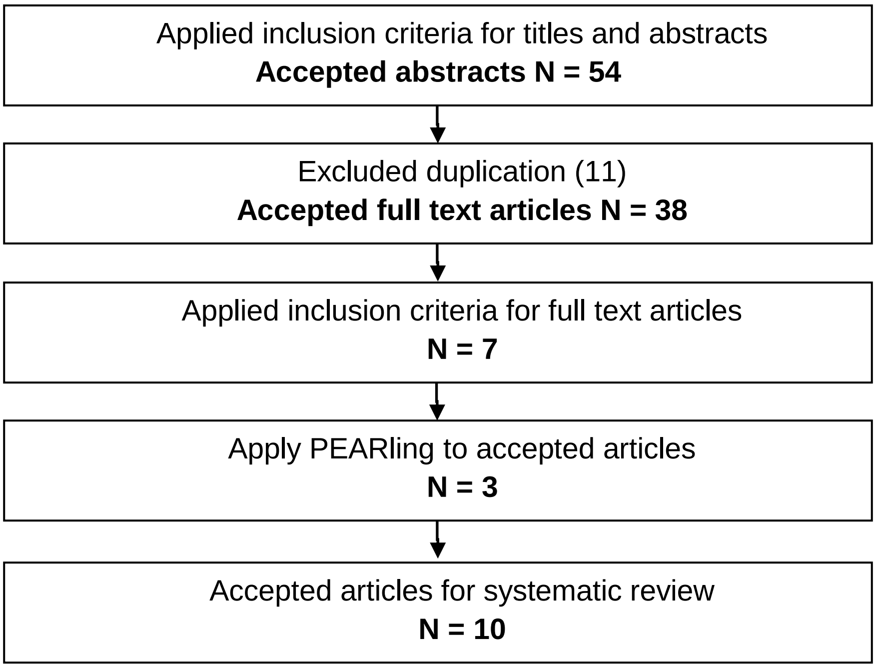

Figure 1: Search Process and Results

General Description of Studies

An overview summary of the included studies is depicted in Table 1. A total of 233 subjects were included in the ten eligible studies. This summary highlights the wide variation between studies with respect to study populations, functional tasks and fatigue protocols applied. Most of the studies[17-21] (60%) was conducted in the USA and all studies were conducted in developed countries. Four of the included studies[14, 15, 20, 21] reported specific lower limb fatigue protocols whilst the remaining six studies[13, 16-19, 22] reported general lower limb and body fatigue protocols.

Table 1: General description of included studies

Author	Country	Population	Sex	Age (Years)	Sample Size	Type of Study	Aim	Fatigue protocol
Nyland *et al*. (1999)	USA	Healthy Athletes	F	18-23	20	Pre-test Post-test Experimental Design	• Effect of induced ham-string muscle fatigue on knee and ankle biodynamics and kinetics during running crossover cut directional change	• Stance leg was fatigued through performing maximal effort eccentric contractions on Biodex machine • Subjects seen as fatigued when a 20% peak torque reduction was seen on Biodex machine
Chappell *et al*. (2005)	USA	Healthy Recreational Athletes	M/F	M 23.7 ± 0.8 F 21.7 ± 2.1	20 (M 10, F 10)	Controlled Laboratory Study	• Determine the effects of lower limb fatigue on the knee kinetics and kinematics of recreational athletes during 3 stop-jump	• 5 Consecutive vertical jumps(from squat position to 115% of participants vertical reach) followed by 30m sprint • Protocol continued until

Author	Country	Population	Sex	Age (Years)	Sample Size	Type of Study	Aim	Fatigue protocol
							tasks	participants reached their own point of exhaustion • Subjects were seen as fatigued when reaching a state of volitional exhaustion
Hollman *et al*. (2012)	USA	Healthy Active Women	F	18-36	40	Controlled Laboratory Study	• To examine whether hip extensor fatigue alters lower extremity kinematics during a jump-landing task in women.	• Experimental group completed a modified Biering-Sørenson fatigue protocol (lay on bed with upper body off end, hold position until fatigued) • Control group performed push-ups until fatigued • Subjects were seen as fatigued when reaching a state of volitional exhaustion

Author	Country	Population	Sex	Age (Years)	Sample Size	Type of Study	Aim	Fatigue protocol
Gehring *et al*. (2008)	Germany	Physically Active Males and Females	M/F	M 25.0 ± 2.4 F 22.6 ± 1.5	26	Controlled Laboratory Study	• Investigate kinematics, kinetics, and active muscle control strategies of the knee joint across gender in fatigue conditions during a landing task	• Participants performed a fatigue protocol using a leg press weight machine • Participants performed knee flexion and extension (90° to full extension) with 50% of their 1 rep max until subjects could not perform the task with selected load • Subjects were seen as fatigued when task could not be performed successfully
Lucci *et al*. (1999)	USA	NCAA Division 1 Female soccer players	F	19.2 ± 0.8	15	Single Group Repeated Measures Design	• To determine biomechanical differences between two fatigue protocols when performing an unanticipated sidestep cutting task	• Functional Agility Short - Term Fatigue Protocol (FAST-FP) • Slow Linear Oxidative Fatigue Protocol (SLO-FP) • Subjects were seen as fatigued when two of the following criteria were met: 1) 90% of age calculated max heart rate reached 2) Respiratory quotient greater than 1.1 3) Plateau in the VO_2 max curve

Author	Country	Population	Sex	Age (Years)	Sample Size	Type of Study	Aim	Fatigue protocol
								4) Volitional exhaustion on part of participant
Moran *et al*. (2006)	Ireland	Physically active male students	M	21.4 ± 1.5	15	Controlled Laboratory Study	• Determine if whole body fatigue: 1) increased peak impact acceleration on the tibia during plyometric drop jumps and • 2) produced associated changes in knee joint kinematics during landing	• Whole body fatigue induced on a treadmill. • Rating of perceived exertion (RPE) was taken at 2 min intervals until participant in fatigued state • Subjects were seen as fatigued when reaching a RPE of 17(very hard)
Pappas *et al*. (2007)	USA	Young active adults	M/F	M 28.8 ± 3.9 F 28.2 ± 5.4	32 (M 16, F 16)	Repeated Measures Experimental Design	• Examine the effect of gender and fatigue on peak values of biomechanical variables during landing from a jump	• Subjects performed 100 consecutive jumps over short obstacles (5-7 cm) and 50 maximal vertical jumps • Subjects were seen as fatigued when they couldn't complete protocol

Author	Country	Population	Sex	Age (Years)	Sample Size	Type of Study	Aim	Fatigue protocol
Nyland *et al*. (1997)	USA	Healthy female college students who were active in intramural athletics	F	21.1 ± 1.64	20	Pre-test Post-test Experimental Design	• Determine the effect of eccentric quadriceps femoris, hamstring, and placebo fatigue on stance limb dynamics during the plant-and-cut phase of a crossover cut.	• Subjects were divided into 4 groups of 5 • Group 1 and 3: Monday (Quadriceps femoris), Wednesday (placebo), and Friday (hamstrings). • Group 2 and 4: Monday (hamstrings), Wednesday (placebo), Friday (quadriceps femoris). • Fatigue protocol for quadriceps and hamstring was the same. On the biodex machine subjects performed maximal effort reps until a 20% peak torque reduction was observed. • Placebo - using a dynamometer in passive isokinetic mode (30°/s for 40 reps). • Subjects were seen as fatigued when a 20% peak torque reduction was seen on Biodex machine
Webster *et al*. (2012)	Australia	Male subjects with and without ACL reconstruction	M	ACL group: 27.0 ± 5.9 Healthy	ACL: 15 Healthy: 11	Controlled Laboratory Study	• To determine the effects of fatigue on lower limb biomechanics during landing in patients who had undergone ACL	• Subjects performed 10 squats (90°), 2 vertical jumps and 10 drop landings (5L, 5R). Repeated 5 times

Author	Country	Population	Sex	Age (Years)	Sample Size	Type of Study	Aim	Fatigue protocol
				group: 22.6 ± 2.6			reconstruction surgery.	• Subjects were seen as fatigued when reaching a state of volitional exhaustion based on a scale of 1 – 10, with 10 being maximum fatigue
Hantes *et al*. (2012)	Greece	Healthy male subjects, both with and without ACL repair	M	Single bundle: 21.1 ± 1 Double bundle: 25.2 ± 6.6 Control: 28 ± 5.4	Single bundle: 12 Double bundle: 12 Control: 10	Controlled Laboratory Study	• To investigate differences in tibial rotation between single- and double-bundle ACL reconstructions after lower limb muscle fatigue	• 5 consecutive max voluntary concentric knee flexion/extensions • 1 min rest, perform consecutive concentric flex/ext until torque dropped below 50% of baseline • Rest 1 min, continue until first 5 repetitions all under 50% of baseline • Subjects were seen as fatigued when a 50% reduction in torqued measured for both muscle groups were observed, compared to baseline torque.

The methodological scores of the identified studies are reported in Table 2. The included studies scored a mean ± SD of 9.7 ± 0.48 on the modified Downs and Black checklist. Notable, none of the studies reported the statistical power and none included representative samples.

Table 2: Methodological appraisal of included studies: Scores attained on Downs and Black appraisal of evidence

Down and Black Criteria	Lucci *et al*. (2011)	Nyland *et al*. (1997)	Nyland *et al*. (1999)	Hollman *et al*. (2012)	Chappell *et al*. (2005)	Pappas *et al*. (2006)	Moran *et al*. (2006)	Gehring *et al*. (2008)	Hantes *et al*. (2012)	Webster *et al*. (2011)
1. Clear aim	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
2. Outcomes described	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
3. Subject described	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
4. Intervention described	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
5. Main findings clearly described	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
6. Measures of random variability	Y	Y	Y	Y	N	Y	N	Y	Y	Y
7. Reporting of probability	Y	N	Y	Y	Y	Y	Y	Y	Y	Y
8. Subjects asked representative of entire population	N	N	N	N	N	N	N	N	N	N
9. Planned analysis	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
10. Appropriate statistics	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
11. Accuracy of outcome measured	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
12. Recruited over the same time	N	N	N	N	N	N	N	N	N	N
13. Statistical power calculations	N	N	N	N	N	N	N	N	N	N
Score	**10**	**9**	**10**	**10**	**9**	**10**	**9**	**10**	**10**	**10**

Knee Biomechanical Outcome Measures

The effect of fatigue protocols on the knee parameters reported in the eligible studies are presented in Table 3. Table 3 illustrates that seven functional movements were analysed in the 10 eligible studies. Only one study, by Chappell *et al*[18] reported on knee kinematics during five of these functional tasks (stop jumps, vertical jumps, bilateral limb drop landing and single limb drop landing). Studies by Moran *et al*[16] and Nyland *et al* (1999)[20] analysed knee kinematics during cutting actions and drop jumps respectively. This illustrates the limited evidence base for the effect of fatigue on knee kinematics for all these functional activities.

Table 3. The effect of fatigue protocols on knee kinematics

Author	Significant Effect Yes/No	p-value or mean difference (95%CI)	Outcome	Effect of fatigue	Time during movement
Cutting Action					
Nyland *et al*. (1997)**	Yes	p ≤ .05	Internal tibial rotation	↑	Peak knee flexion
Nyland *et al*. (1997)**	Yes	p ≤ .01	Peak knee flexion	↓	Not stated
Nyland *et al*. (1999)**	Yes	p = .014	Mean knee internal rotation velocity	↑	Phase1: Between heel strike and impact absorption
Nyland *et al*. (1999)**	Yes	p = .012	Maximum knee internal rotation	↓	Phase 2: Initial propulsion in new direction
Lucci *et al*. (1999)**	Yes	p = .022	Knee flexion	↓	Not stated
Lucci *et al*. (1999)**	Yes	p < .001	Knee internal rotation: FAST-FP and SLO-FP	↑	Throughout movement
Lucci *et al*. (1999)**	Yes	p = .017	Knee flexion	↓	Peak vertical ground reaction
Lucci *et al*. (1999)**	Yes	p = .037	Knee internal rotation	↑	Peak posterior ground reaction
Lucci *et al*. (1999)**	Yes	p = .001	Knee flexion	↓	Peak stance

Author	Significant Effect Yes/No	p-value or mean difference (95%CI)	Outcome	Effect of fatigue	Time during movement
Drop Jumps					
Moran *et al*. (2006)*	Yes	p = .02	Tibial peak acceleration at 30 cm drop height	↑	Not stated
Moran *et al*. (2006)*	No	p = .30	Tibial peak acceleration at 50 cm drop height	↑	Not stated
Moran *et al*. (2006)*	Yes	p = .02	Peak knee flexion at 50 cm drop height	↑	Peak knee flexion
Moran *et al*. (2006)*	Yes	p = .00	Knee peak angular velocity at 30 cm drop height	↑	Eccentric phase
Moran *et al*. (2006)*	No	p = .13	Knee peak angular velocity at 50 cm drop height	↑	Eccentric phase
Pappas *et al*. (2007)***	Yes	p = .001	Peak knee valgus: Females vs Males	↑	Landing
Pappas *et al*. (2007)***	Yes	p = .003	Peak VGRF: Females vs Males	↑	Landing
Pappas *et al*. (2007)***	Yes	p = .038	Peak VGRF	↑	Not stated
Pappas *et al*. (2007)***	Yes	p = .018	Peak rectus femoris activity	↑	Not stated
Stop Jumps					
Chappell *et al*. (2005)***	Yes	p = .01	Peak proximal tibial anterior shear force	↑	Landing
Chappell *et al*. (2005)***	Yes	p = 001	Peak proximal tibial anterior shear force: Female vs Male	↑	Landing
Chappell *et al*. (2005)***	Yes	p = .03	Knee flexion angles	↓	Landing
Chappell *et al*. (2005)***	Yes	p = .001	Knee flexion angles: Females vs Males	↓	Peak proximal anterior tibial shear force
Vertical Jumps					
Hollman *et al*. (2012)**	Yes	p = .006	Knee flexion	↑	Not stated
Hollman *et al*. (2012)**	Yes	p = .015	Knee medial rotation	↓	Not stated
Hollman *et al*. (2012)**	Yes	p = .029	Group main effect: Knee varus/valgus	↑	Not stated
Bilateral Limb Drop Landing					
Gehring *et al*. (2008)***	Yes	p < .05	Pre-activation of medial hamstring	↓	Not stated
Gehring *et al*. (2008)***	Yes	p < .001	Pre-activation of lateral hamstring	↓	Not stated
Gehring *et al*. (2008)***	Yes	p < .05	Pre-activation of gastrocnemius	↓	Not stated
Gehring *et al*. (2008)***	Yes	p = .02	Vastus lateralis muscle activation: Females vs Males	↓	Not stated
Gehring *et al*. (2008)***	Yes	p = .049	Biceps femoris muscle activation: Females vs Males	↓	Not stated
Gehring *et al*. (2008)***	Yes	p = .001	Maximum knee flexion angle: Females vs Males	↑	Landing
Gehring *et al*. (2008)***	Yes	p = .049	Abduction/adduction onset angles: Females vs Males	↑	Landing
Gehring *et al*. (2008)***	Yes	p = .007	Maximum knee adduction angles: Females vs Males	↑	Landing
Gehring *et al*. (2008)***	Yes	p = .004	Maximum knee flexion angles	↑	200ms after foot contact

Author	Significant Effect Yes/No	p-value or mean difference (95%CI)	Outcome	Effect of fatigue	Time during movement
Single Limb Drop Landing					
Webster et al. (2012)*	Yes	1.8 (-1.0 to 5.0) vs 2.1 (0.4 to 4.3)	Peak knee abduction at 50% fatigue: Control limb vs ACL reconstructed limb	↑	Landing
Webster et al. (2012)*	Yes	1.3 (-1.0 to 3.8) vs 2.5 (0.5 to 4.6)	Peak knee abduction at 100% fatigue: Control limb vs ACL reconstructed limb	↑	Landing
Webster et al. (2012)*	Yes	26.9 (22.6 to 31.2) vs 23.5 (19.9 to 27.2)	Peak knee internal rotation at 50% fatigue: Control limb vs ACL reconstructed limb	↓	Landing
Webster et al. (2012)*	Yes	27.9 (23.2 to 32.8) vs 23.9 (19.8 to 28.1)	Peak knee internal rotation at 100% fatigue: Control limb vs ACL reconstructed limb	↓	Landing
Webster et al. (2012)*	Yes	26.2 (21.9 to 30.6) vs 23.5 (19.9 to 27.2)	Peak knee internal rotation at 50% fatigue: Contralateral limb vs ACL reconstructed limb	↓	Landing
Webster et al. (2012)*	Yes	25.7 (21.6 to 29.9) vs 23.9 (19.8 to 28.1)	Peak knee internal rotation at 100% fatigue: Contralateral limb vs ACL reconstructed limb	↓	Landing
Rotational Movements					
Hantes *et al*. (2012)*	Yes	p = .015	Tibial rotation: single-bundle group	↑	Not stated
Hantes *et al*. (2012)*	No	p = .6	Tibial rotation: Double-bundle group	↑	Not stated
Hantes *et al*. (2012)*	No	p =.85	Tibial rotation: Control group	↑	Not stated
Hantes et al. (2012)*	Yes	p = .03	Tibial rotation: Single-bundle vs Double-bundle group	↑	Not Stated

* Studies including only males

** Studies including only females

*** Studies including both males and females

Figure 2 illustrates the pre-and post-fatigue knee angles at peak knee flexion and initial contact for healthy participants. The plots indicate that none of the studies reported a significant difference in knee flexion angles at peak knee flexion and initial contact following the fatigue protocols

	Post-fatigue			Pre-fatigue			Mean Difference
Study or Subgroup	**Mean**	**SD**	**Total**	**Mean**	**SD**	**Total**	**IV, Random, 95% CI**
1.1.1 Peak knee flexion angle							
Gehring et al 2008 (fem)	90	2	13	87.6	2.7	13	2.40 [0.57, 4.23]
Gehring et al 2008(males)	78.3	3.7	13	71.8	3.1	13	6.50 [3.88, 9.12]
Lucci et al 1999 (FAST-FP	-48.28	7.36	15	-53.07	7.04	15	4.79 [-0.36, 9.94]
Lucci et al 1999 (SLO-FP)	-51.19	6.38	15	-54.53	5.14	15	3.34 [-0.81, 7.49]
Nyland et al 1999	57.3	10	20	57.8	9	20	-0.50 [-6.40, 5.40]
1.1.2 Knee flexion angle at initial contact							
Gehring et al 2008 (fem)	16.5	1.5	13	15.9	1.7	13	0.60 [-0.63, 1.83]
Gehring et al 2008(males)	16.7	1.4	13	15.9	1.7	13	0.80 [-0.40, 2.00]
Lucci et al 1999 (FAST-FP	-22.3	7.1	15	-25.5	8	15	3.20 [-2.21, 8.61]
Lucci et al 1999 (SLO-FP)	-22.6	9.7	15	-25.8	5.7	15	3.20 [-2.49, 8.89]
Nyland et al 1999	19.8	10	20	19.3	9	20	0.50 [-5.40, 6.40]

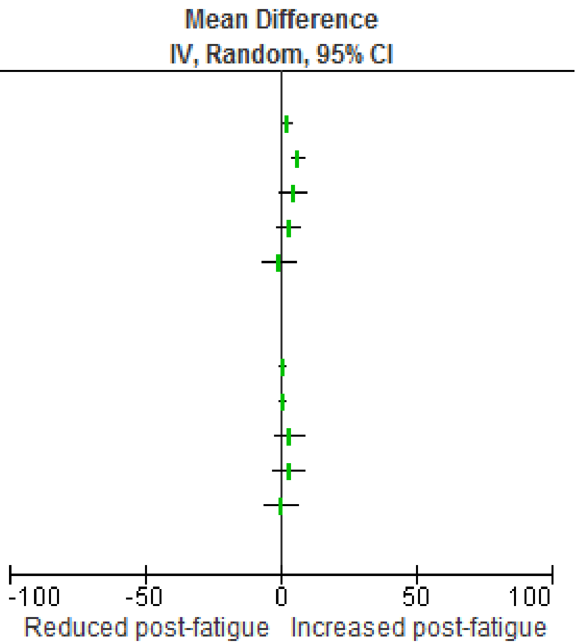

Figure 2: Pre- and Post-Fatigue - Knee Flexion Angles at peak knee flexion and initial contact for healthy participants.

Table 4 indicates the effects of fatigue protocols on knee moments in eligible studies. One study, Webster *et al*[13], reported statistically significant differences for all reported movements. Hantes *et al*[14] reported no significant difference in knee moments post-fatigue. Two studies, Nyland *et al* (1999)[21] and Nyland *et al* (1997)[22] showed mixed results with some movements being significantly affected by the fatigue protocols.

Table 4. Pre- and Post-fatigue knee moments

Studies		Variety	0% Fatigued	50% Fatigued	100% Fatigued	Statistically significant
WEBSTER et al. (2012)	ACL Recon-structed Limb	Peak knee flexion, $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$	1.09 (0.97-1.25)	1.08 (0.95-1.21)	0.98 (0.85-1.12)	Yes
		Peak knee adduction, $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$	0.85 (0.61-1.08)	0.77 (0.54-0.99)	0.75 (0.55-0.97)	Yes
	Contra-lateral Limb	Peak knee flexion, $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$	1.30 (1.11-1.43)	1.20 (1.05-1.35)	1.04 (0.89-1.19)	Yes
		Peak knee adduction, $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$	1.03 (0.84-1.21)	0.92 (0.69-1.15)	0.91 (0.68-1.14)	Yes
	Control	Peak knee flexion, $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$	1.06 (0.87-1.24)	0.95 (0.80-1.11)	0.89 (0.74-1.05)	Yes
		Peak knee adduction, $N{\cdot}m{\cdot}kg^{-1}{\cdot}m^{-1}$	0.52 (0.25-0.79)	0.53 (0.27-0.80)	0.43 (0.18-0.68)	Yes

Studies		Variety	0% Fatigued	50% Fatigued	100% Fatigued	Statistically significant
HANTES et al. (2012)	Control Group	Rotational moment, N·mm/ kg	456.3 ± 133.8	n.a.	410.9 ± 116.8	No
HANTES et al. (2012)	Single-Bundle Group	Rotational moment, N·mm/ kg	339.2 ± 147.9	n.a.	387.6 ± 130.8	No
HANTES et al. (2012)	Double-Bundle Group	Rotational moment, N·mm/ kg	317.9 ± 97.1	n.a.	407.9 ± 187.2	No
NYLAND et al. (1997)	Quadriceps fatigue	Peak impact knee flexion, Nm	-40.8 ± 21.4	n.a.	-36.8 ± 20.5	No
NYLAND et al. (1997)	Quadriceps fatigue	Peak knee extension, Nm	127.3 ± 35.8	n.a.	109.2 ± 42.4	Yes ($p = .01$)
NYLAND et al. (1997)	Quadriceps fatigue	Peak propulsive knee flexion, NM	-58.5 ± 25.4	n.a.	-56.1 ± 24.5	Yes ($p = .05$)
NYLAND et al. (1997)	Quadriceps fatigue	Peak knee abduction, Nm	129 ± 65.6	n.a.	114.4 ± 49.8	No
NYLAND et al. (1997)	Quadriceps fatigue	Peak knee adduction, Nm	-57.5 ± 44	n.a.	-55.4 ± 35.8	No
NYLAND et al. (1997)	Quadriceps fatigue	Peak knee external rotation, Nm	-140.8 ± 27.2	n.a.	-127.7 ± 21.2	Yes ($p = .002$)

Studies			Variety	0% Fatigued	50% Fatigued	100% Fatigued	Statistically significant
NYLAND et al. (1997)	Hamstring fatigue		Peak impact knee flexion, Nm	-39.7 ± 27.4	n.a.	-30.3 ± 23	Yes (p = .01)
			Peak knee extension, Nm	124.8 ± 41.4	n.a.	121.4 ±29.8	Yes (p = .036)
			Peak propulsive knee flexion, NM	-58.6 ± 22	n.a.	-55.5 ± 19.2	Yes (p = .04)
			Peak knee abduction, Nm	110.7 ± 46.3	n.a.	110.3 ± 53.1	No
			Peak knee adduction, Nm	-53 ± 31.8	n.a.	-42.8 ± 32.4	No
			Peak knee external rotation, Nm	-145.4 ± 27.9	n.a.	-140.3 ± 35.7	No
LUCCI et al. (2011)	Fast - FP	Initial Contact	Knee flexion (-) / extension (+), N·m/ kg	0.000 ± 0.170	n.a.	0.080 ± 0.240	No
			Knee abduction (-) / adduction (+), N·m/ kg	0.070 ± 0.090	n.a.	0.070 ± 0.080	No
		Peak Stance	Knee flexion (-) / extension (+), N·m/ kg	1.920 ± 0.280	n.a.	1.880 ± 0.290	No
			Knee abduction (-) / adduction (+), N·m/ kg	0.430 ± 0.360	n.a.	0.370 ± 0.270	No

Studies			Variety	0% Fatigued	50% Fatigued	100% Fatigued	Statistically significant
LUCCI et al. (2011)	Slow - FP	Initial Contact	Knee flexion (-) / extension (+), N·m/ kg	-0.020 ± 0.170	n.a.	0.010 ± 0.190	No
			Knee abduction (-) / adduction (+), N·m/ kg	0.060 ± 0.060	n.a.	0.050 ± 0.060	No
		Peak Stance	Knee flexion (-) / extension (+), N·m/ kg	2.110 ± 0.300	n.a.	1.950 ± 0.270	No
			Knee abduction (-) / adduction (+), N·m/ kg	0.420 ± 0.400	n.a.	0.290 ± 0.160	No

Webster reports data as: Mean (95% confidence interval)

Hantes reports data as: Mean ± SD

Nyland reports data as: Mean ± SD

Lucci reports data as: Mean ± SD

$N \cdot m \cdot kg^{-1} \cdot m^{-1}$	Nuton Meters per Kilogram Meters
N·mm/ kg	Nuton Millimetres per Kilogram
Nm	Nuton Meters
N·m/ kg	Nuton Meters per Kilogram

DISCUSSION

This review synthesised the current evidence on the effect of fatigue protocols on knee control during functional activities. The findings of this review indicate that fatigue generally seams to affect knee control negatively across various fatigue protocols.

A variety of fatigue protocols were used during the eligible studies. Fatigue protocols ranged from single lower limb fatigue, bilateral lower limb fatigue and also whole body fatigue. Furthermore, some studies used specific measurements to indicate when participants were fatigued whilst other studies relied on the participant's own perceived point of exhaustion.[18] These factors could have influenced the effect on knee biomechanics measured. Due to the small evidence base, it was not possible to sub-group different fatigue protocols. Future research into the effect of fatigue protocols on knee control should possibly focus on the effect of specific fatigue protocols as more research becomes available.

In 2008, Shimokochi and Schultz[24] reported on the mechanisms that could lead to non-contact ACL injuries. The mechanisms highlighted by these authors included increased knee valgus, increased internal rotation, decreased knee flexion, and increased knee moments. This review found that non-contact ACL injuries tend to happen during decelerating or accelerating motions with excessive quadriceps contractions and decreased hamstring contractions at or near full knee extension. Furthermore the review stated that the load on the ACL is higher when a valgus load was combined with internal rotation compared to external rotation. Lastly it was reported that excessive valgus loads during weight-bearing, and decelerating activities increases the load on the ACL.

An increase in knee internal rotation was reported by Nyland *et al*[21], Lucci *et al*[22] and Hantes *et al*[14]. Nyland *et al*[21] reported this increase following the fatigue protocol at peak knee flexion. Contrary, three of the studies[13, 19, 20] reported a statistically significant decrease in knee internal rotation. However, knee internal rotation was measured at different times during the functional activities and this could explain the contradictory findings. In addition, Webster et al[13] assessed single limb drop landings from different heights while Hantes et al[14] assessed a rotational movement with stance leg in full extension. However the findings of this review raises the possibility that fatigue could have an effect on internal rotation in healthy knees and this could increase ACL injury risk. It is however not possible to draw a clear conclusion whether ACL reconstructed knees are more adversely affected by fatigue compared to healthy knees as there is limited research published on the effect of fatigue on ACL reconstructed limbs at this time.

Two studies[13, 19] reported a significant increase in knee valgus following the respected fatigue protocols. Webster *et al*[13] reported this increase at 50% and 100% fatigue for the ACL reconstructed limb when compared with both the contra-lateral and control limb. This could indicate that fatigue negatively affects knee valgus during functional activities for both healthy and ACL reconstructed knees. In a 2008 study, Shimokochi and Schultz[24] reported that increased knee valgus may be a risk factor for ACL injuries. Further research is required before conclusive findings can be drawn.

The findings of studies reporting on knee moments were inconsistent. Statistically significant differences were reported by Lucci *et al*[22], Webster *et al*[13], Chappel *et al*[18] and Nyland *et al*[21]. Two studies[22, 13] reported decreased knee moments following fatigue protocols whilst two studies[18, 21] reported increased knee moments. Three studies[14, 21, 22] reported no statistically significant differences in knee moments post fatigue. It is important to note that two studies[21, 22] reported on several different knee moments, of which some were significant statistically whilst others were not. The study by Chappel et al[18] was not included in Table 5 as the relevant pre- and post-fatigue knee moment values were not reported fully. The statistical significance was however reported. In 2010, Santamaria and Webster[25] reported similar findings as the current review. It was reported that in some of the studies fatigue influenced knee moments whilst no influence was reported in the other included studies.

The importance of knee flexion angles during deceleration was highlighted by Shimokochi *et al*[24]. It was reported that a decrease in knee flexion during deceleration movements such as side-stepping and landing could increase the risk of injury to the ACL. The results reported in the excepted studies do not draw a clear picture of the effect that fatigue has on knee flexion angles as the results reported were conflicting. Nyland *et al*[21] reported a significant decrease in knee flexion angles at peak knee flexion. Lucci *et al*[22] reported a decrease in knee flexion angles at peak stance and peak vertical ground reaction force. Knee flexion angles also decreased following fatigue according to Chappel *et al*[18]. Hollman *et al*[19], Gehring *et al*[15] and Moran *et al*[16] all reported a statistically significant increase in knee flexion angles post fatigue.

Meta-analysis could be applied to the results on knee flexion angles at peak knee flexion and initial contact of three studies[15, 20, 22]. The forest plot (figure 2) shows no significant difference in pre- and post-fatigue knee flexion angles. Based on the reported results it appears that the specific fatigue protocol, functional activity being assessed and time during movement all play a role in whether knee flexion is negatively affected by fatigue.

Previous studies[25, 27, 35] have reported on the gender differences in relation to knee/ACL injuries. Of the included studies only three studies[15, 17, 18] included both male and female participants, whilst three studies[13, 14, 16] included only male participants and four studies[19-22] included only female participants. This makes it difficult to get a clear result on whether females are more susceptible to the effects of fatigue compared with males. The included studies reporting on gender differences[15, 17, 18] reports similar findings as earlier studies[25, 27, 35]. Chappell *et al*[18] reported an increase in the peak proximal tibial anterior shear force during bilateral landing in both males and female. Females however, showed a mean increase of 94% in the peak proximal tibial anterior shear force compared to males. Pappas *et al*[17] found that females landed with greater peak knee valgus and vertical ground reaction force compared with males. Gehring *et al*[15] concluded that gender differences in knee flexion velocity, abduction angle and muscle activation suggested that females and males possess different neuromuscular strategies in controlling the knee joint in dynamic landing movements.

Excessive anterior force combined with a decrease in knee flexion angle might place the ACL under tremendous strain which may lead to ACL injury[24]. An increase in the anterior tibial shear force following fatigue protocols were reported in some of the included studies[16, 18, 20]. The increase in the anterior shear forces reported could be attributed to decreased or altered muscle activity following fatigue protocols. Included studies[15, 17, 19] reported alterations to both muscle activity and the rate of activation of specific muscles. These results were further influenced by factors such as gender, the specific fatigue protocol and whether the knee being evaluated was a healthy knee or an ACL reconstructed knee.

Two of the included studies[13, 14] reported on the effects of fatigue on knee control in participants with prior ACL reconstructions. A shortcoming of these studies was the fact that only male participants were used. Gender differences can thus not be assessed. Future research should include both male and female participants to be more representative. The participants assessed by Webster *et al*[13] underwent ACL surgery 15-19 months prior to their participation in the study. Hantes *et al*[14] included participants who underwent surgery between January 2008 and December 2009. The date of participation was not stated, but there was a possibility of participants' surgery dates differing by up to 2 years. The participants in the two studies[13, 14] were thus not at the same stage of recovery which could potentially influence the results of the studies. If possible, future studies utilising participants who have undergone ACL surgery should possibly use participants within the same timeframe of healing/rehabilitation to eliminate the time from surgery possibly affecting the results.

The effects of fatigue protocols on knee control reported in the included studies have provided implications for clinical practice. The review highlights that females might be more susceptible to the influence of fatigue on knee control during rotational and landing activities.[19-22] Injury prevention programmes should focus on correcting knee kinematics during specific activities during training and fatigue should be incorporated in the rehabilitation program.

Only one of the included studies used unanticipated movements in their examination.[22] It is an important consideration for rehabilitation as not all movements during sporting activities are anticipated. Future research should focus on both anticipated and unanticipated movements during testing as it would give clearer real world results. Taking these results of this review into account during training in real life scenarios could cause a drastic decrease in the number of ACL injuries occurring during sporting activities. The limitations of the review are that only studies in the English language were reviewed. In addition, due to heterogeneity, a meta-analysis of most outcomes was not possible.

CONCLUSION

Fatigue generally seams to affect knee control negatively across various fatigue protocols. Inability to synthesize more data in a meta-analysis makes it difficult to come to a concrete conclusion. Gender differences was also highlighted in the results of three of the included studies. These studies highlighted several outcomes where females were more affected by fatigue than males. Future research should possibly look at using a standardised fatigue protocol to get more accurate and consistent results during the different functional activities. Participants should also be of similar stature, as the current studies included both recreational athletes and athletes consistently competing at a high level. Future research should also focus more on using participants with previous ACL injuries or reconstructions as these types of studies are still limited.

Clinical Message

- Some knee biomechanics are altered when functional movements are performed under fatigued conditions.
- Clinicians should consider gender differences, a possible standardised fatigue protocol and the inclusion of more ACL reconstruction subjects in future research.

Competing Interests

The authors declare that they have no competing interests.

Chapter 3: Conclusions

The aim of the current study was to determine the effect that general and local fatigue protocols have on knee control during functional activities such as cutting manoeuvres, rotational movements, drop jumps and stop jump tasks which are most commonly found in multidirectional sports.

Prior to conducting the systematic review, ethical approval was obtained from the Health Research Ethics Committee (HREC). The approval letter is attached as Appendix B.

The main findings of the current systematic review, was that fatigue does have an effect on some knee parameters during the functional activities. The results were at times conflicting, especially for knee flexion and knee internal rotation. Both an increase and decrease in knee internal rotation was reported in the included studies. Knee flexion provided the most conflicting results as the results differed across the different studies and time during the movements. A combination of increased internal rotation and decreased knee flexion could increase the risk of ACL ruptures as it could increase the strain on the ACL. Another main finding of the current review was the gender differences seen in the included studies. In all of the studies reporting on gender differences it was evident that females were more susceptible to the effects of fatigue on knee control which could put them at a greater risk of ACL injury during functional activities.

Previous literature reported similar findings as the current review. In August 2010, a systematic review was published by Santamaria and Webster.[25] As in the current review, it was reported that methodological differences in the included studies made synthesis of evidence challenging. Santamaria and Webster[25] reported that fatigue did, in some cases, negatively affect knee valgus and rotation which could indicate an increased risk of knee injury. Similar results were found in the current review. This review was limited to studies on single-limb landings and did not focus on any of the other high risk movements. The authors recommended that future studies should focus on fatigue protocols that introduce fatigue locally and centrally. In addition, the authors suggest that further reviews should include subjects who are recovering from injury or surgery. These suggestions were taken into account during the current review and formed part of the inclusion criteria.

The results of the current review tend to suggest that fatigue is detrimental to knee control during some functional activities and can increase the risk of sustaining serious ACL injuries or ruptures. Ruptures of the ACL mostly require surgical repair. Following ACLR surgery most athletes only return to sport after lengthy layoffs if ever. Therefore clinicians and trainers should take great care in developing injury prevention or rehabilitation programs. Focus should be placed on correct landing and directional changing biomechanics. The corresponding muscle balances should also be focussed on to avoid agonist and antagonist imbalance. Special care should also be taken in female training programs as females seem to be more prone to ACL injuries than their male counterparts.

Some limitations to the current review were the sample size reported in studies, the fatigue protocols, the low number of studies reporting on ACL reconstructed knees and the fact that all the studies were laboratory based and does not necessarily provide the same situations as in real match conditions. Future research should include larger samples of participants and also include both male and female participants in studies on ACL reconstructed knees. Furthermore it would be advisable to use participants from both elite and recreational sports in the same study. Lastly, it could be beneficial to develop a standardised fatigue protocol as to ascertain what the effect of such a protocol would be on different multidirectional movements.

Some valid results were reported during the current review. Clinicians should take these findings into account when developing training programs as this can potentially lead to a reduction in knee injuries in both recreational and professional sports.

REFERENCES

1. Cochrane JL, Lloyd DG, Buttfield A, Seward H, McGivern J. **Characteristics of anterior cruciate ligament injuries in Australian football.** Journal of Science and Medicine in Sport 2007. Issue **10**:96—104
2. Alentorn-Geli E, Myer GD, Silvers HJ, Samitier G, Romero D, La´zaro-Haro C, Cugat R. **Prevention of non-contact anterior cruciate ligament injuries in soccer players. Part 1: Mechanisms of injury and underlying risk factors**. Knee Surg Sports TraumatolArthrosc 200. Issue **17**:705–729. DOI: 10.1007/s00167-009-0813-1
3. Dragoo JL, Braun HJ, Durham JL, Chen MR, Harris AHS. **Incidence and Risk Factors for Injuries to the Anterior Cruciate Ligament in National Collegiate Athletic Association Football: Data From the 2004-2005 Through 2008-2009 National Collegiate Athletic Association Injury Surveillance System**. Am J Sports Med 2012. Issue **40**: 990. DOI: 10.1177/0363546512442336
4. Palmieri-Smith RM, Thomas AC, Wojtys EM. **Maximizing Quadriceps Strength After ACL Reconstruction**. Clin Sports Med 2008. Issue **27**: 405-424
5. Peck KY, Johnston DA, Owens BD, Cameron KL. **The Incidence of Injury Among Male and Female Intercollegiate Rugby Players**. Sports Health: A Multidisciplinary Approach 2013. Issue **5**: 327. DOI: 10.1177/1941738113487165
6. Bizzini M, Hancock D, Impellizzeri F. **Suggestions from the Field for Return to Sports Participation Following Anterior Cruciate Ligament Reconstruction: Soccer**. Journal of Orthopaedic & Sports Physical Therapy 2012. Issue **42**: 304. DOI:10.2519/jospt.2012.4005
7. Mihata LCS, Beutler AI, Boden BP. **Comparing the Incidence of Anterior Cruciate Ligament Injury in Collegiate Lacrosse, Soccer, and Basketball Players : Implications for Anterior Cruciate Ligament Mechanism and Prevention**. Am J Sports Med 2006. Issue **34**: 899. DOI: 10.1177/0363546505285582
8. Roos H, Ornell M, Gärdsell P, Lohmander LS, Lindstrand A. **Soccer After Anterior Cruciate Ligament Injury— an Incompatible Combination? A National Survey of Incidence and Risk Factors and a 7-year Follow-up of 310 players**. ActaOrthopaedica 1995. Issue **66**: 2, 107 — 112. DOI: 10.3109/17453679508995501

9. Hewett TE, Di Stasi SL, Myer GD. **Current Concepts for Injury Prevention in Athletes After Anterior Cruciate Ligament Reconstruction**. The American Journal of Sports Medicine 2013. Issue **41**: 216. DOI: 10.1177/0363546512459638
10. Gabbett TJ, **Incidence, Site and Nature of Injuries in Amateur Rugby League Over Three Consecutive Seasons**. British Journal of Sports Medicine 2000. Issue **34**: 98.
11. Junge A, Langevoort G, Pipe A, Peytavin A, Wong F, Mountjoy M, Beltrami G, Terrell R, Holzgraefe M, Charles R, Dvorak J. **Injuries in Team Sport Tournaments During the 2004 Olympic Games**. The American Journal of Sports Medicine 2006. Issue (34), **4**: 565. DOI: 10.1177/0363546505281807
12. Waldén M, Hägglund M, EkstrandJ.**High Risk of New Knee Injuries in Elite Footballers With Previous Anterior Cruciate Ligament Injury**. British Journal of Sports Medicine 2006. Issue (40), **2**: 158. DOI: org/10.1136/bjsm.2005.021055
13. Webster KE, Santamaria LJ, McClelland JA, Feller JA. **Effect of Fatigue on Landing Biomechanics after Anterior Cruciate Ligament Reconstruction Surgery**. Medicine and Science in Sports and Exercise 2012. Vol. 44, No. **5**: 910–916. DOI: 10.1249/MSS.0b013e31823fe28d
14. Hantes ME, Tsarouhas A, Giakas G, Spiropoulos G, Sideris V, Christel P, Malizos KN. **Effect of Fatigue on Tibial Rotation After Single- and Double-Bundle Anterior Cruciate Ligament Reconstruction: A 3-Dimensional Kinematic and Kinetic Matched-Group Analysis**. The American Journal of Sports Medicine 2012. Issue 40, **9:** 2045. DOI: 10.1177/0363546512454413
15. Gehring D, Melnyk M, Gollhofer A. **Gender and Fatigue Have Influence on Knee Joint Control Strategies During Landing**. Clinical Biomechanics 2009. Vol.**24**: 82-87. DOI: 10.1016/j.clinbiomech.2008.07.005
16. Moran KA, Marshall BM. **Effect of Fatigue on Tibial Impact Accelerations and Knee Kinematics in Drop Jumps**. Medicine & Science in Sports & Exercise 2006. Vol. 38, No **10**: 1836-1842. DOI: 10.1249/01.mss.0000229567.09661.20
17. Pappas E, Sheikhzadeh A, Hagins M, Nordin M. **The Effect of Gender and Fatigue on the Biomechanics of Bilateral Landings from a Jump: Peak Values**. Journal of Sports Science and Medicine 2007. Vol. **6**: 77-84.

18. Chappell JD, Herman DC, Knight BS, Kirkendall DT, Garrett WE, Yu B. **Effect of Fatigue on Knee Kinetics and Kinematics in Stop-Jump Tasks**. The American Journal of Sports Medicine 2005. Vol. 33, No **7**: 1022-1029. DOI: 10.1177/0363546504273047
19. Hollman JH, Hohl JM, Kraft JL, Strauss JD, Traver KJ. **Effects of Hip Extensor Fatigue on Lower Extremity Kinematics During a Jump-Landing Task in Women: A Controlled Laboratory Study**. Clinical Biomechanics 2012. Vol. **27**: 903-909. DOI: 10.1016/j.clinbiomech.2012.07.004
20. Nyland JA, Caborn DNM, Shapiro R, Johnson DL. **Crossover Cutting During Hamstring Fatigue Produces Transverse Plane Knee Control Deficits**. Journal of Athletic Training 1999. Vol. 34, No **2**: 137-143.
21. Nyland JA, Shapiro R, Caborn DNM, Nitz AJ, Malone TR. **The Effect of Quadriceps Femoris, Hamstring, and Placebo Eccentric Fatigue on Knee and Ankle Dynamic During Crossover Cutting**. Journal of Orthopaedic & Sports Physical Therapy 1997. Vol. 25, No **3**: 171-184.
22. Lucci S, Cortes N, Van Lunen B, Ringleb S, Onate J. **Knee and Hip Sagittal and Transverse Plane Changes After Two Fatigue Protocols**. Journal of Science and Medicine in Sport 2011. Vol. **14**: 453-459. DOI: 10.1016/j.jsams.2011.05.001
23. Shin CS, Chaudhari AM, Andriacchi TP. **Valgus Plus Internal Rotation Moments Increase Anterior Cruciate Ligament Strain More Than Either Alone**. Medicine & Science in Sports & Exercise 2011. Vol. 43, No**. 8**: 1484–1491. DOI: 10.1249/MSS.0b013e31820f8395
24. Shimokochi Y, Shultz SJ. **Mechanisms of Noncontact Anterior Cruciate Ligament Injury**. Journal of Athletic Training 2008. Vol. 43, No **4**: 396-408. DOI: 10.4085/1062-6050-43.4.396
25. Santamaria LJ, Webster KE. **The Effect of Fatigue on Lower-Limb Biomechanics During Single-Limb Landings: A Systematic Review**. The Journal of Orthopaedic & Sports Physical Therapy 2010. Vol. 40, No **8**: 464-473. DOI: 10.2519/jospt.2010.3295.
26. Changela PK, Selvamani K, Ramaprabhu. **A Study to Evaluate the Effect of Fatigue on Knee Joint Proprioseption and Balance in Healthy Individuals**. International Journal of Engineering Research and Applications 2012. Vol. 2, No **2**: 645-649. ISSN: 2248-9622.

27. Waldén M, Hägglund M, Magnusson H, Ekstrand J. **Anterior Cruciate Ligament Injury in Elite Football: a Prospective Three-Cohort Study**. Knee Surgery, Sports Traumatology, Arthroscopy 2011. Vol. **19**: 11-19. DOI: 10.1007/s00167-010-1170-9.
28. Gobbi A, Mahajan V, Karnatzikos G, Nakamura N. **Single- Versus Double-Bundle ACL Reconstruction: Is There Any Difference in Stability and Function at 3-year Followup**. Clinical Orthopaedics and Related Research 2012. **470**: 824-834. DOI: 10.1007/s11999-011-1940-9
29. Nicolini AP, Carvalho RT, Matsuda MM, SayumFilho J, Cohen M. **Common Injuries in Athletes' Knee: Experience of a Specialized Center**. ActaOrtopédicaBrasileira 2014. Vol. 22, No **3**: 127-131. DOI: http://dx.doi.org/10.1590/1413-78522014220300475.
30. Aglietti P, Giron F, Losco M, Cuomo P, Ciardullo A, Mondanelli N. **Comparison Between Single- and Double-Bundle Anterior Cruciate Ligament Reconstruction: a Prospective, Randomized, Single-Blinded Clinical Trail**. The American Journal of Sports Medicine 2010. Vol. 38, No **1**: 25-34. DOI: 10.1177/0363546509347096
31. Gobbi A, Francisco R. **Factors Affecting Return to Sport After Anterior Cruciate Ligament Reconstruction with Patellar Tendon and Hamstring Graft: a Prospective Clinical Investigation**. Knee Surgery, Sports Traumatology, Arthroscopy 2006. Vol. **14**: 1021–1028. DOI: 10.1007/s00167-006-0050-9.
32. Erickson BJ, Harris JD, Heninger JR, Frank R, Bush-Joseph CA, Verma NN, Cole BJ, Bach BA. **Performance and Return-to-Sport After ACL Reconstruction in NFL Quarterbacks**. Orthopedics 2014. Vol. 37. No **8**: 728-734. DOI: 10.3928/01477447-20140728-59.
33. Harris JD, Erickson BJ, Bach BR Jr, Abrams GD, Cvetanovich GL, Forsythe B, McCormick FM, Gupta AK, Cole BJ.**Return-to-Sport and Performance After Anterior Cruciate Ligament Reconstruction in National Basketball Association Players**. Sports Health 2013. Vol. 5, No **6**: 562-568. DOI: 10.1177/1941738113495788
34. Laible C, Shermann OH. **Risk Factors and Prevention Strategies of Non-Contact Anterior Cruciate Ligament Injuries**. Bulletin of the Hospital for Joint Diseases 2014. Vol. 72, No **1**: 70-75.
35. Waldén M, Hägglund M, Werner J, Ekstrand J. **The Epidemiology of Anterior Cruciate Ligament Injury in Football (Soccer): a Review of the Literature from a Gender-Related**

Perspective. Knee Surgery, Sports Traumatology, Arthroscopy 2011. Vol. **19**: 3-10. DOI: 10.1007/s00167-010-1172-7.

36. Zantop T, Petersen W, Sekiya JK, Musahl V, Fu FH. **Anterior Cruciate Ligament Anatomy and Function Relating to Anatomical Reconstruction**. Knee Surgery, Sports Traumatology, Arthroscopy 2006. Vol. **14**: 982-992. DOI: 10.1007/s00167-006-0076-z
37. Greig M, Siegler JC. **Soccer-Specific Fatigue and Eccentric Hamstring Muscle Strength**. Journal of Athletic Training 2009. Vol. 44, no **2**: 180-184.
38. Prodromos CC, Han Y, Rogowski J, Joyce B, Shi K. **A Meta-analysis of the Incidence of Anterior Cruciate Ligament Tears as a Function of Gender, Sport, and a Knee-Injury Reduction Regimen**. Arthroscopy: The Journal of Arthroscopic and Related Surgery 2007. Vol. 23, No **12**: 1320-1325. DOI: 10.1016/j.arthro.2007.07.003.
39. Corin G, Strutton PH, McGregor AH. **Establishment of a protocol to test the fatigue of the trunk muscles.** Brittish Journal of Sports Medicine 2005. Vol. 39, No **10**: 731-735. DOI: 10.1136/bjsm.2004.015537
40. **American Academy of Orthopaedic Surgeons, OrthoInfo.** [http://orthoinfo.aaos.org/topic.cfm?topic=a00297]
41. **University of California, San Francisco, Department of Orthopaedic Surgery Website [http://tumor.informatics.jax.org/mtbwi/index.do]**
42. Kakarlapudi TK, Bickerstaff DR. **Knee instability, isolated and complex.** Western Journal of Medicine 2001. Vol. 174, No 4: 266-272

Appendix A: Journal Guidelines

Instructions for authors

Research articles

Criteria | Submission process | Preparing main manuscript text | Preparing illustrations and figures |Preparing tables | Preparing additional files | Style and language

Assistance with the process of manuscript preparation and submission is available from BioMed Central customer support team. See 'About this journal' for information about policies and the refereeing process. We also provide a collection of links to useful tools and resources for scientific authors on our page.

Criteria

Research articles should report on original primary research, but may report on systematic reviews of published research provided they adhere to the appropriate reporting guidelines which are detailed in our Editorial Policies. Please note that non-commissioned pooled analyses of selected published research will not be considered.

Submission process

Manuscripts must be submitted by one of the authors of the manuscript, and should not be submitted by anyone on their behalf. The submitting author takes responsibility for the article during submission and peer review.

Please note that *BMC Musculoskeletal Disorders* levies an article-processing charge on all accepted Research articles; if the submitting author's institution is a BioMed Central member the cost of the article-processing charge may be covered by the membership (see About page for detail). Please note that the membership is only automatically recognised on submission if the submitting author is based at the member institution.

To facilitate rapid publication and to minimize administrative costs, *BMC Musculoskeletal Disorders*prefers online submission.

Files can be submitted as a batch, or one by one. The submission process can be interrupted at any time; when users return to the site, they can carry on where they left off.

See below for examples of word processor and graphics file formats that can be accepted for the main manuscript document by the online submission system. Additional files of any type, such as movies, animations, or original data files, can also be submitted as part of the manuscript.
During submission you will be asked to provide a cover letter. Use this to explain why your manuscript should be published in the journal, to elaborate on any issues relating to our editorial policies in the'About *BMC Musculoskeletal Disorders*' page, and to declare any potential competing interests.
You will be also asked to provide the contact details (including email addresses) of potential peer reviewers for your manuscript. These should be experts in their field, who will be able to provide an objective assessment of the manuscript. Any suggested peer reviewers should not have published with any of the authors of the manuscript within the past five years, should not be current collaborators, and should not be members of the same research institution. Suggested reviewers will be considered alongside potential reviewers recommended by the Editorial team, Editorial Advisors, Section Editors and Associate Editors.
Assistance with the process of manuscript preparation and submission is available from BioMed Central customer support team.
We also provide a collection of links to useful tools and resources for scientific authors on our Useful Tools page.

File formats

The following word processor file formats are acceptable for the main manuscript document:

- Microsoft word (DOC, DOCX)
- Rich text format (RTF)
- Portable document format (PDF)
- TeX/LaTeX (use BioMed Central's TeX template)
- DeVice Independent format (DVI)

TeX/LaTeX users: Please use BioMed Central's TeX template and BibTeXstylefile if you use TeX format. During the TeX submission process, please submit your TeX file as the main manuscript file and your bib/bbl file as a dependent file. Please also convert your TeX file into a PDF and submit this PDF as an additional file with the name 'Reference PDF'. This PDF will be used by internal staff as a reference point to check the layout of the article as the author intended. Please also note that all figures must be coded at the end of the TeX file and not inline.
If you have used another template for your manuscript, or if you do not wish to use BibTeX, then please submit your manuscript as a DVI file. We do not recommend converting to RTF.

For all TeX submissions, all relevant editable source must be submitted during the submission process. Failing to submit these source files will cause unnecessary delays in the publication procedures.

Publishing Datasets

Through a special arrangement with Lab Archives, LLC, authors submitting manuscripts to BMC Musculoskeletal Disorders can obtain a complimentary subscription to Lab Archives with an allotment of 100MB of storage. Lab Archives is an Electronic Laboratory Notebook which will enable scientists to share and publish data files in situ; you can then link your paper to these data. Data files linked to published articles are assigned digital object identifiers (DOIs) and will remain available in perpetuity. Use of Lab Archives or similar data publishing services does not replace pre-existing data deposition requirements, such as for nucleic acid sequences, protein sequences and atomic coordinates. Instructions on assigning DOIs to datasets, so they can be permanently linked to publications, can be found on the Lab Archives website. Use of Lab Archives' software has no influence on the editorial decision to accept or reject a manuscript.

Authors linking datasets to their publications should include an Availability of supporting data section in their manuscript and cite the dataset in their reference list.

Preparing main manuscript text

General guidelines of the journal's style and language are given below.

Overview of manuscript sections for Research articles

Manuscripts for Research articles submitted to *BMC Musculoskeletal Disorders* should be divided into the following sections (in this order):

- Title page
- Abstract
- Keywords
- Background
- Methods
- Results and discussion
- Conclusions
- List of abbreviations used (if any)
- Competing interests
- Authors' contributions
- Authors' information
- Acknowledgements
- Endnotes
- References
- Illustrations and figures (if any)
- Tables and captions

- Preparing additional files

The **Accession Numbers** of any nucleic acid sequences, protein sequences or atomic coordinates cited in the manuscript should be provided, in square brackets and include the corresponding database name; for example, [EMBL:AB026295, EMBL:AC137000, DDBJ:AE000812, GenBank:U49845, PDB:1BFM, Swiss-Prot:Q96KQ7, PIR:S66116].

The databases for which we can provide direct links are: EMBL Nucleotide Sequence Database (EMBL), DNA Data Bank of Japan (DDBJ), GenBank at the NCBI (GenBank), Protein Data Bank (PDB), Protein Information Resource (PIR) and the Swiss-Prot Protein Database (Swiss-Prot).

You can download a template (Mac and Windows compatible; Microsoft Word 98/2000) for your article.

For reporting standards please see the information in the About section.

Title page

The title page should:

- provide the title of the article
- list the full names, institutional addresses and email addresses for all authors
- indicate the corresponding author

Please note:

- the title should include the study design, for example "A versus B in the treatment of C: a randomized controlled trial X is a risk factor for Y: a case control study"
- abbreviations within the title should be avoided

Abstract

The Abstract of the manuscript should not exceed 350 words and must be structured into separate sections: **Background,** the context and purpose of the study; **Methods**, how the study was performed and statistical tests used; **Results**, the main findings; **Conclusions**, brief summary and potential implications. Please minimize the use of abbreviations and do not cite references in the abstract. **Trial registration**, if your research article reports the results of a controlled health care intervention, please list your trial registry, along with the unique identifying number (e.g. **Trial registration**: Current Controlled Trials ISRCTN73824458). Please note that there should be no space between the letters and numbers of your trial registration number. We recommend manuscripts that report randomized controlled trials follow the CONSORT extension for abstracts.

Keywords

Three to ten keywords representing the main content of the article.

Background

The Background section should be written in a way that is accessible to researchers without specialist knowledge in that area and must clearly state - and, if helpful, illustrate - the background to the research and its aims. Reports of clinical research should, where appropriate, include a summary of a search of the literature to indicate why this study was necessary and what it aimed to contribute to the field. The section should end with a brief statement of what is being reported in the article.

Methods

The methods section should include the design of the study, the setting, the type of participants or materials involved, a clear description of all interventions and comparisons, and the type of analysis used, including a power calculation if appropriate. Generic drug names should generally be used. When proprietary brands are used in research, include the brand names in parentheses in the Methods section.

For studies involving human participants a statement detailing ethical approval and consent should be included in the methods section. For further details of the journal's editorial policies and ethical guidelines see 'About this journal'.
For further details of the journal's data-release policy, see the policy section in 'About this journal'.

Results and discussion

The Results and discussion may be combined into a single section or presented separately. Results of statistical analysis should include, where appropriate, relative and absolute risks or risk reductions, and confidence intervals. The Results and discussion sections may also be broken into subsections with short, informative headings.

Conclusions

This should state clearly the main conclusions of the research and give a clear explanation of their importance and relevance. Summary illustrations may be included.

List of abbreviations

If abbreviations are used in the text they should be defined in the text at first use, and a list of abbreviations can be provided, which should precede the competing interests and authors' contributions.

Competing interests

A competing interest exists when your interpretation of data or presentation of information may be influenced by your personal or financial relationship with other people or organizations. Authors must disclose any financial competing interests; they should also reveal any non-financial competing interests that may cause them embarrassment were they to become public after the publication of the manuscript.

Authors are required to complete a declaration of competing interests. All competing interests that are declared will be listed at the end of published articles. Where an author gives no competing interests, the listing will read 'The author(s) declare that they have no competing interests'.

When completing your declaration, please consider the following questions:

Financial competing interests

- In the past five years have you received reimbursements, fees, funding, or salary from an organization that may in any way gain or lose financially from the publication of this manuscript, either now or in the future? Is such an organization financing this manuscript (including the article-processing charge)? If so, please specify.
- Do you hold any stocks or shares in an organization that may in any way gain or lose financially from the publication of this manuscript, either now or in the future? If so, please specify.
- Do you hold or are you currently applying for any patents relating to the content of the manuscript? Have you received reimbursements, fees, funding, or salary from an organization that holds or has applied for patents relating to the content of the manuscript? If so, please specify.
- Do you have any other financial competing interests? If so, please specify.

Non-financial competing interests

Are there any non-financial competing interests (political, personal, religious, ideological, academic, intellectual, commercial or any other) to declare in relation to this manuscript? If so, please specify.

If you are unsure as to whether you, or one your co-authors, has a competing interest please discuss it with the editorial office.

Authors' contributions

In order to give appropriate credit to each author of a paper, the individual contributions of authors to the manuscript should be specified in this section.

According to ICMJE guidelines, An 'author' is generally considered to be someone who has made substantive intellectual contributions to a published study. To qualify as an author one should 1) have made substantial contributions to conception and design, or acquisition of data, or analysis and interpretation of data; 2) have been involved in drafting the manuscript or revising it critically for important intellectual content; 3) have given final approval of the version to be published; and 4) agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. Each author should have participated sufficiently in the work to take public responsibility for appropriate portions of the content.

Acquisition of funding, collection of data, or general supervision of the research group, alone, does not justify authorship.

We suggest the following kind of format (please use initials to refer to each author's contribution): AB carried out the molecular genetic studies, participated in the sequence alignment and drafted the manuscript. JY carried out the immunoassays. MT participated in the sequence alignment. ES participated in the design of the study and performed the statistical analysis. FG conceived of the study, and participated in its design and coordination and helped to draft the manuscript. All authors read and approved the final manuscript.

All contributors who do not meet the criteria for authorship should be listed in an acknowledgements section. Examples of those who might be acknowledged include a person who provided purely technical help, writing assistance, or a department chair who provided only general support.

Authors' information

You may choose to use this section to include any relevant information about the author(s) that may aid the reader's interpretation of the article, and understand the standpoint of the author(s). This may include details about the authors' qualifications, current positions they hold at institutions or societies, or any other relevant background information. Please refer to authors using their initials. Note this section should not be used to describe any competing interests.

Acknowledgements

Please acknowledge anyone who contributed towards the article by making substantial contributions to conception, design, acquisition of data, or analysis and interpretation of data, or who was involved in drafting the manuscript or revising it critically for important intellectual content, but who does not meet the criteria for authorship. Please also include the source(s) of funding for each author, and for the manuscript preparation. Authors must describe the role of the funding body, if any, in design, in the collection, analysis, and interpretation of data; in the writing of the manuscript; and in the decision to submit the manuscript for publication. Please also acknowledge anyone who contributed materials essential for the study. If a language editor has made significant revision of the manuscript, we recommend that you acknowledge the editor by name, where possible.

The role of a scientific (medical) writer must be included in the acknowledgements section, including their source(s) of funding. We suggest wording such as 'We thank Jane Doe who provided medical writing services on behalf of XYZ Pharmaceuticals Ltd.'

Authors should obtain permission to acknowledge from all those mentioned in the Acknowledgements section.

Endnotes

Endnotes should be designated within the text using a superscript lowercase letter and all notes (along with their corresponding letter) should be included in the Endnotes section. Please format this section in a paragraph rather than a list.

References

All references, including URLs, must be numbered consecutively, in square brackets, in the order in which they are cited in the text, followed by any in tables or legends. Each reference must have an individual reference number. Please avoid excessive referencing. If automatic numbering systems are used, the reference numbers must be finalized and the bibliography must be fully formatted before submission.

Only articles, datasets, clinical trial registration records and abstracts that have been published or are in press, or are available through public e-print/preprint servers, may be cited; unpublished abstracts, unpublished data and personal communications should not be included in the reference list, but may be included in the text and referred to as "unpublished observations" or "personal communications" giving the names of the involved researchers. Obtaining permission to quote personal communications and unpublished data from the cited colleagues is the responsibility of the author. Footnotes are not allowed, but endnotes are permitted. Journal abbreviations follow Index Medicus/MEDLINE. Citations in the reference list should include all named authors, up to the first 30 before adding '*et al.*'..

Any *in press* articles cited within the references and necessary for the reviewers' assessment of the manuscript should be made available if requested by the editorial office.

Style files are available for use with popular bibliographic management software:

- BibTeX
- EndNote style file
- Reference Manager
- Zotero

Examples of the *BMC Musculoskeletal Disorders* reference style are shown below. Please ensure that the reference style is followed precisely; if the references are not in the correct style they may have to be retyped and carefully proofread.

All web links and URLs, including links to the authors' own websites, should be given a reference number and included in the reference list rather than within the text of the manuscript. They should be provided in full, including both the title of the site and the URL, in the following format: **The Mouse Tumor Biology Database** [http://tumor.informatics.jax.org/mtbwi/index.do]. If an author or group of authors can clearly be associated with a web link, such as for weblogs, then they should be included in the reference.

Examples of the *BMC Musculoskeletal Disorders* reference style

Article within a journal

Koonin EV, Altschul SF, Bork P: **BRCA1 protein products: functional motifs.** *Nat Genet* 1996,**13:**266-267.

Article within a journal supplement

Orengo CA, Bray JE, Hubbard T, LoConte L, Sillitoe I: **Analysis and assessment of ab initio three-dimensional prediction, secondary structure, and contacts prediction.** *Proteins* 1999, **43**(Suppl 3):149-170.

In press article

Kharitonov SA, Barnes PJ: **Clinical aspects of exhaled nitric oxide.** *EurRespir J*, in press.

Published abstract

Zvaifler NJ, Burger JA, Marinova-Mutafchieva L, Taylor P, Maini RN: **Mesenchymal cells, stromal derived factor-1 and rheumatoid arthritis [abstract].** *Arthritis Rheum* 1999, **42:**s250.

Article within conference proceedings

Jones X: **Zeolites and synthetic mechanisms.** In *Proceedings of the First National Conference on Porous Sieves: 27-30 June 1996; Baltimore.* Edited by Smith Y. Stoneham: Butterworth-Heinemann; 1996:16-27.

Book chapter, or article within a book

Schnepf E: **From prey via endosymbiont to plastids: comparative studies in dinoflagellates.** In*Origins of Plastids.Volume 2.* 2nd edition.Edited by Lewin RA. New York: Chapman and Hall; 1993:53-76.

Whole issue of journal

Ponder B, Johnston S, Chodosh L (Eds): **Innovative oncology.** In *Breast Cancer Res* 1998, **10:**1-72.

Whole conference proceedings

Smith Y (Ed): *Proceedings of the First National Conference on Porous Sieves: 27-30 June 1996; Baltimore.* Stoneham: Butterworth-Heinemann; 1996.

Complete book

Margulis L: *Origin of Eukaryotic Cells.* New Haven: Yale University Press; 1970.

Monograph or book in a series

Hunninghake GW, Gadek JE: **The alveolar macrophage.** In *Cultured Human Cells and Tissues.* Edited by Harris TJR. New York: Academic Press; 1995:54-56. [Stoner G (Series Editor): *Methods and Perspectives in Cell Biology,* vol 1.]

Book with institutional author

Advisory Committee on Genetic Modification: *Annual Report.* London; 1999.

PhD thesis

Kohavi R: **Wrappers for performance enhancement and oblivious decision graphs.** *PhD thesis.*Stanford University, Computer Science Department; 1995.

Link / URL

The Mouse Tumor Biology Database [http://tumor.informatics.jax.org/mtbwi/index.do]

Link / URL with author(s)

Corpas M: **The Crowdfunding Genome Project: a personal genomics community with open source values** [http://blogs.biomedcentral.com/bmcblog/2012/07/16/the-crowdfunding-genome-project-a-personal-genomics-community-with-open-source-values/]

Dataset with persistent identifier

Zheng, L-Y; Guo, X-S; He, B; Sun, L-J; Peng, Y; Dong, S-S; Liu, T-F; Jiang, S; Ramachandran, S; Liu, C-M; Jing, H-C (2011): **Genome data from sweet and grain sorghum (Sorghum bicolor)**.*GigaScience Database*. http://dx.doi.org/10.5524/100012.

Clinical trial registration record with persistent identifier

Mendelow, AD (2006): **Surgical Trial in Lobar Intracerebral Haemorrhage**. Current Controlled Trials. http://dx.doi.org/10.1186/ISRCTN22153967

Preparing illustrations and figures

Illustrations should be provided as separate files, not embedded in the text file. Each figure should include a single illustration and should fit on a single page in portrait format. If a figure consists of separate parts, it is important that a single composite illustration file be submitted which contains all parts of the figure. There is no charge for the use of color figures.

Please read our figure preparation guidelines for detailed instructions on maximising the quality of yourfigures.

Formats

The following file formats can be accepted:

- PDF (preferred format for diagrams)
- DOCX/DOC (single page only)
- PPTX/PPT (single slide only)
- EPS
- PNG (preferred format for photos or images)
- TIFF
- JPEG
- BMP

Figure legends

The legends should be included in the main manuscript text file at the end of the document, rather than being a part of the figure file. For each figure, the following information should be provided: Figure number (in sequence, using Arabic numerals - i.e. Figure 1, 2, 3etc); short title of figure (maximum 15 words); detailed legend, up to 300 words.

Please note that it is the responsibility of the author(s) to obtain permission from the copyright holder to reproduce figures or tables that have previously been published elsewhere.

Preparing tables

Each table should be numbered and cited in sequence using Arabic numerals (i.e. Table 1, 2, 3 etc.). Tables should also have a title (above the table) that summarizes the whole table; it should be no longer than 15 words. Detailed legends may then follow, but they should be concise. Tables should always be cited in text in consecutive numerical order.

Smaller tables considered to be integral to the manuscript can be pasted into the end of the document text file, in A4 portrait or landscape format. These will be typeset and displayed in the final published form of the article. Such tables should be formatted using the 'Table object' in a word processing program to ensure that columns of data are kept aligned when the file is sent electronically for review; this will not always be the case if columns are generated by simply using tabs to separate text. Columns and rows of data should be made visibly distinct by ensuring that the borders of each cell display as black lines. Commas should not be used to indicate numerical values. Color and shading may not be used; parts of the table can be highlighted using symbols or bold text, the meaning of which should be explained in a table legend. Tables should not be embedded as figures or spreadsheet files.

Larger datasets or tables too wide for a portrait page can be uploaded separately as additional files. Additional files will not be displayed in the final, laid-out PDF of the article, but a link will be provided to the files as supplied by the author.

Tabular data provided as additional files can be uploaded as an Excel spreadsheet (.xls) or comma separated values (.csv). As with all files, please use the standard file extensions.

Preparing additional files

Although *BMC Musculoskeletal Disorders* does not restrict the length and quantity of data included in an article, we encourage authors to provide datasets, tables, movies, or other information as additional files.

Please note: All Additional files **will be published** along with the article. Do not include files such as patient consent forms, certificates of language editing, or revised versions of the main manuscript document with tracked changes. Such files should be sent by email to editorial@biomedcentral.com, quoting the Manuscript ID number.

Results that would otherwise be indicated as "data not shown" can and should be included as additional files. Since many weblinks and URLs rapidly become broken, *BMC Musculoskeletal Disorders* requires that supporting data are included as additional files, or deposited in a recognized repository. Please do not link to data on a personal/departmental website. The maximum file size for additional files is 20 MB each, and files will be virus-scanned on submission.

Additional files can be in any format, and will be downloadable from the final published article as supplied by the author. We recommend CSV rather than PDF for tabular data.

Certain supported files formats are recognized and can be displayed to the user in the browser. These include most movie formats (for users with the Quicktime plugin), mini-websites prepared according to our guidelines, chemical structure files (MOL, PDB), geographic data files (KML).

If additional material is provided, please list the following information in a separate section of the manuscript text:

- File name (e.g. Additional file 1)
- File format including the correct file extension for example .pdf, .xls, .txt, .pptx (including name and a URL of an appropriate viewer if format is unusual)
- Title of data
- Description of data

Additional files should be named "Additional file 1" and so on and should be referenced explicitly by file name within the body of the article, e.g. 'An additional movie file shows this in more detail [see Additional file 1]'.

Additional file formats

Ideally, file formats for additional files should not be platform-specific, and should be viewable using free or widely available tools. The following are examples of suitable formats.

- Additional documentation
  - PDF (Adode Acrobat)
- Animations
  - SWF (Shockwave Flash)
- Movies
  - MP4 (MPEG 4)

- MOV (Quicktime)
- Tabular data
  - XLS, XLSX (Excel Spreadsheet)
  - CSV (Comma separated values)

As with figure files, files should be given the standard file extensions.

Mini-websites

Small self-contained websites can be submitted as additional files, in such a way that they will be browsable from within the full text HTML version of the article. In order to do this, please follow these instructions:

1. Create a folder containing a starting file called index.html (or index.htm) in the root.
2. Put all files necessary for viewing the mini-website within the folder, or sub-folders.
3. Ensure that all links are relative (ie "images/picture.jpg" rather than "/images/picture.jpg" or "http://yourdomain.net/images/picture.jpg" or "C:\Documents and Settings\username\My Documents\mini-website\images\picture.jpg") and no link is longer than 255 characters.
4. Access the index.html file and browse around the mini-website, to ensure that the most commonly used browsers (Internet Explorer and Firefox) are able to view all parts of the mini-website without problems, it is ideal to check this on a different machine.
5. Compress the folder into a ZIP, check the file size is under 20 MB, ensure that index.html is in the root of the ZIP, and that the file has .zip extension, then submit as an additional file with your article.

Style and language

General

Currently, *BMC Musculoskeletal Disorders* can only accept manuscripts written in English. Spelling should be US English or British English, but not a mixture.
There is no explicit limit on the length of articles submitted, but authors are encouraged to be concise.

BMC Musculoskeletal Disorders will not edit submitted manuscripts for style or language; reviewers may advise rejection of a manuscript if it is compromised by grammatical errors. Authors are advised to write clearly and simply, and to have their article checked by colleagues before submission. In-house copyediting will be minimal. Non-native speakers of English may choose to make use of a copyediting service.

Language editing

For authors who wish to have the language in their manuscript edited by a native-English speaker with scientific expertise, BioMed Central recommends Edanz. BioMed Central has arranged a 10% discount to the fee charged to BioMed Central authors by Edanz. Use of an editing service is neither a requirement nor a guarantee of acceptance for publication. Please contact Edanz directly to make arrangements for editing, and for pricing and payment details.

Help and advice on scientific writing

The abstract is one of the most important parts of a manuscript. For guidance, please visit our page onWriting titles and abstracts for scientific articles.

Tim Albert has produced for BioMed Central a list of tips for writing a scientific manuscript. American Scientist also provides a list of resources for science writing. For more detailed guidance on preparing a manuscript and writing in English, please visit the BioMed Central author academy.

Abbreviations

Abbreviations should be used as sparingly as possible. They should be defined when first used and a list of abbreviations can be provided following the main manuscript text.

Typography

- Please use double line spacing.
- Type the text unjustified, without hyphenating words at line breaks.
- Use hard returns only to end headings and paragraphs, not to rearrange lines.
- Capitalize only the first word, and proper nouns, in the title.
- All lines and pages should be numbered. Authors are asked to ensure that line numbering is included in the main text file of their manuscript at the time of submission to facilitate peer-review. Once a manuscript has been accepted, line numbering should be removed from the manuscript before publication. For authors submitting their manuscript in Microsoft Word please do not insert page breaks in your manuscript to ensure page numbering is consistent between your text file and the PDF generated from your submission and used in the review process.
- Use the *BMC Musculoskeletal Disorders* reference format.
- Footnotes are not allowed, but endnotes are permitted.
- Please do not format the text in multiple columns.
- Greek and other special characters may be included. If you are unable to reproduce a particular special character, please type out the name of the symbol in full. **Please ensure that all special characters used are embedded in the text, otherwise they will be lost during conversion to PDF.**

Units

SI units should be used throughout (liter and molar are permitted, however).

Appendix B: Ethics Exemption

UNIVERSITEIT·STELLENBOSCH·UNIVERSITY
jou kennisvennoot • your knowledge partner

Ethics Letter

22-Jul-2014

Ethics Reference #: X14/06/009
Clinical Trial Reference #:
Title: The effect of fatigue protocols on knee biomechanics during functional tasks: A systematic review.

Dear Mr Jaco PRETORIUS,

Thank you for your application to our Health Research Ethics Committee (HREC). This application is for a systematic review.

The Health Research Ethics Committee considers this proposal to be exempt from ethical review.

This letter confirms that this research is now registered and you can proceed with study related activities.

If you have any queries or need further assistance, please contact the HREC Office 0219389657.

Sincerely,

REC Coordinator
Franklin Weber
Health Research Ethics Committee 1

Appendix C: Modified Downs and Black Check List

ALL CRITERIA	DESCRIPTION OF CRITERIA (with additional explanation as required, determined by consensus of raters)	POSSIBLE ANSWERS
1	Is the hypothesis/aim/objective of the study clearly described? Must be explicit	Yes/No
2	Are the main outcomes to be measured clearly described in the Introduction or Methods section? If the main outcomes are first mentioned in the Results section, the question should be answered no. ALL primary outcomes should be described for YES	Yes/No
3	Are the characteristics of the patients included in the study clearly described? In cohort studies and trials, inclusion and/or exclusion criteria should be given. In case-control studies, a case-definition and the source for controls should be given. Single case studies must state source of patient	Yes/No
4	Are the interventions of interest clearly described? Treatments and placebo (where relevant) that are to be compared should be clearly described.	Yes/No
5	Are the main findings of the study clearly described? Simple outcome data (including denominators and numerators) should be reported for all major findings so that the reader can check the major analyses and conclusions.	Yes/No
6	Does the study provide estimates of the random variability in the data for the main outcomes? In non normally distributed data the inter-quartile range of results should be reported. In normally distributed data the standard error, standard deviation or confidence intervals should be reported	Yes/No
7	Have actual probability values been reported (e.g. 0.035 rather than <0.05) for the main outcomes except where the probability value is less than 0.001?	Yes/No
8	Were the subjects asked to participate in the study representative of the entire population from which they were recruited? The study must identify the source population for patients and describe how the patients were selected.	Yes/No/ UTD
9	If any of the results of the study were based on "data dredging", was this made clear? Any analyses that had not been planned at the outset of the study should be clearly indicated. Retrospective = NO. Prospective = YES	Yes/No/ UTD
10	Were the statistical tests used to assess the main outcomes appropriate? The statistical techniques used must be appropriate to the data. If no tests done, but would have been appropriate to do = NO	Yes/No/UTD
11	Were the main outcome measures used accurate (valid and reliable)? Where outcome measures are clearly described, which refer to other work or that demonstrates the outcome measures are accurate = YES. ALL primary outcomes valid and reliable for YES	Yes/No/ UTD
12	Were study subjects in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same time? For a study which does not specify the time period over which patients were recruited, the question should be answered as UTD. Surgical studies must be <10 years for YES, if >10 years then NO	Yes/No/ UTD
13	Did the study have sufficient power to detect a clinically important effect where the probability value for a difference being due to chance <5% Sample sizes have been calculated to detect a difference of x% and y%.	1-5

Appendix D: JBI Data Extraction Form for Experimental/Observational Studies

JBI Data Extraction Form for Experimental/ Observational Studies

Reviewer:
Author:
Journal:
Title:

Date:
Year:
Record Number:

Study Method

RCT
Quasi-RCT
Longitudinal
Retrospective
Observational

Other: ______________________

Participants

Setting ______________________
Population ______________________
Mean Age ______________________

Sample Size
Intervention 1 ____________ Intervention 2 ____________ Intervention 3 ____________

Interventions

Intervention 1 ______________________

Intervention 2 ______________________

Intervention 3 ______________________

Clinical Outcome Measures

Outcome Description	Scale/ Measure

Study Results

(a) Dichotomous Data

Outcome	Onset of lateral thigh muscles: Male vs female	Statistical diff

(b) Continuous Data

Outcome	Females: Pre (intv1) and Post (intv 2) fatigue	Males: Pre (intv 1) and Post (intv 2) fatigue

Author's Conclusions

Comments

Appendix E: Examples of Search Strategies Used

<u>Pubmed search (Healthy subjects)</u>

1. Knee control
2. Knee stability
3. Dynamic knee stability
4. Knee kinetics
5. Knee proprioception
6. Knee biomechanics
7. Knee kinematics
8. #1 OR #2 OR #3 OR #4 OR #5 OR #6 OR #7
9. Fatigue
10. Muscle fatigue
11. #9 OR #10
12. Healthy adults
13. #8 AND #11 AND #12

Pubmed search (ACL injured subjects)

1. Knee control
2. Knee stability
3. Dynamic knee stability
4. Knee kinetics
5. Knee proprioception
6. Knee biomechanics
7. Knee kinematics
8. #1 OR #2 OR #3 OR #4 OR #5 OR #6 OR #7
9. Fatigue
10. Muscle fatigue
11. #9 OR #10
12. ACL reconstruction
13. Anterior Cruciate Ligament reconstruction
14. ACL repair
15. Anterior Cruciate Ligament repair
16. #12 OR #13 OR #14 OR #15
17. #8 AND #11 AND #16

Cochrane Library (Healthy subjects)

1. (Fatigue OR muscle fatigue) AND (knee control OR knee biomechanics) AND healthy adults

Cochrane Library (ACL injured subjects)

1. (Fatigue OR muscle fatigue) AND (knee control OR knee biomechanics) AND (ACL repair OR ACL reconstruction)

Science Direct (Healthy subjects)

1. Knee control AND Fatigue AND Healthy Adults

Science Direct (ACL injured subjects)

1. Knee Control AND Fatigue AND (ACL reconstruction OR ACL repair)