2010

Patellar Tendon Loading During Dynamic Landings: How this is Moderated by Fatigue and the Presence of a Patellar Tendon Abnormality

Suzi Edwards

University of Wollongong

Recommended Citation
Edwards, Suzi, Patellar Tendon Loading During Dynamic Landings: How this is Moderated by Fatigue and the Presence of a Patellar Tendon Abnormality, Doctorate of Philosophy thesis, School of Health Sciences, University of Wollongong, 2010.
http://ro.uow.edu.au/theses/3205

Research Online is the open access institutional repository for the University of Wollongong. For further information contact Manager Repository Services: morgan@uow.edu.au.
NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.
Patellar Tendon Loading During Dynamic Landings:
How this is Moderated by Fatigue and the Presence of a Patellar Tendon Abnormality

A thesis submitted in fulfilment of the requirements for the award of the degree

Doctorate of Philosophy
from
University of Wollongong
by
Suzi Edwards
BAppSc (Ex Sport Sc), MSc (Hons)

School of Health Sciences
2010
Dedication

I dedicate this thesis to my parents, Bev and Bill Edwards. Through all the hard times that I have endured, you have been by my side providing me with unconditional love and support in helping me achieve my dreams. I love you so much and I thank you from my heart for everything that you have done for Zale and I.
I, Suzi Edwards, declare that this thesis “Patellar Tendon Loading During Dynamic Landings: How this is Moderated by Fatigue and the Presence of a Patellar Tendon Abnormality”, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Health Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged in this thesis. This thesis has not been submitted for a degree at any other university or institution.

Suzi Edwards

17 February 2010
Publications

This thesis is composed of chapters that have been written as journal articles and includes:


As the primary, supervisor, I, Professor Julie Steele, declare that the greater part of the work in each article listed above is attributed to the candidate, Suzi Edwards. In each of the above manuscripts, Suzi has contributed to study design, was solely responsible for data collection and data analysis, and was largely responsible for data interpretation.
The first draft of each manuscript was written by the candidate and Suzi was then responsible for responding to the editorial suggestions of her co-authors. The co-authors, Julie Steele (Chapters 2-7), Deirdre McGhee (Chapters 2-7), Jill Cook (Chapters 2-7) and Craig Purdam (Chapters 2-7) were responsible for assisting in study design, data interpretation and editing in the manuscripts. Bridget Munro (Chapter 2) assisted in study design and editing in the manuscript. Sue Beattie was responsible for data collection of the ultrasonographic images of the patellar tendons. Suzi has been solely responsible for submitting each manuscript for publication to the relevant journals, and she has been primarily in charge of responding to reviewer’s comments, with assistance from her co-authors.

Suzi Edwards
Candidate
17 February 2010

Professor Julie R Steele
Primary Supervisor
17 February 2010
Acknowledgements

I would like to express my sincere thanks to all the following people without whose assistance this thesis would not have been possible.

My biggest thanks of all are to my beautiful little chatterbox son Zale who has been by my side throughout this journey. He has given me all the cuddles, hugs, laughs and love that I needed to brighten up my day, especially when he sings his song about how he loves his mummy and his dog Zebra. No longer will he hear his Mum say that she is still at Uni or, most importantly, that we can’t afford to buy things!

In completing this thesis, I wish to thank my primary supervisor Professor Julie Steele for her foresight, support and enthusiasm, which has been instrumental in shaping my future direction. Despite my colourful path that I have encountered in completing my PhD thesis, Julie has offered her guidance and persistence to get me through it and, most importantly, she has developed my skills and knowledge to become an independent and lateral thinking researcher and biomechanist. For everything, thank you.

I am extremely indebted for my co-supervisor Deirdre McGhee, not only her guidance and assistance through her diverse knowledge and experience, but who taught me how to write manuscripts and kept my thesis moving along.

Thank you also to my co-supervisors Associate Professor Jill Cook and Craig Purdam whose expansive wealth of knowledge has given added depth to my PhD thesis. Without your input, this thesis would have not reached the potential that it has.

I would also like to thank the members of the Biomechanics Research Laboratory who assisted with testing, John Whitting, Laura Buckley, Catherine Wild, and Karen Mickle.

I am very grateful to all of the participants who volunteered their time and bodies for testing, and came back for retesting despite the severe muscle soreness that they sustained each time.

Special thanks to the New South Wales Sporting Injury Committee (Australia) for their foresight, belief in the project and financial support.
Abstract

BACKGROUND

Patellar tendinopathy is a complex overuse knee injury common in sports involving repetitive jumping and landing, in which repetitive loading is the most frequently reported causative factor associated with patellar tendinopathy. In order to provide evidence for the development of prevention and rehabilitation programs for patellar tendinopathy, research is required to broaden our understanding of the risk factors associated with patellar tendinopathy.

THESIS AIM

The primary purpose of this thesis was to systematically investigate and characterise the patellar tendon loading generated during dynamic landings, and the influence of fatigue and the presence of a patellar tendon abnormality on diagnostic imaging (PTA) on these loads.

METHOD

To achieve the thesis aim, the thesis was completed in three parts. Part I (Chapter 2) assessed whether lower limb symmetry during a stop-jump landing task in 16 male athletes with normal patellar tendons could be assumed. Then the validity and reliability of an experimental protocol designed to induce lower limb fatigue was assessed (Chapter 3), in which 13 healthy male athletes performed the fatigue protocol on three separate occasions. The participants performed sets of 30 submaximal stretch-shortening cycle efforts immediately followed by 30 seconds rest during which the participants’ kinetics and kinematics were quantified and blood lactate samples recorded. The experimental protocol that was developed in Part I (Chapter 2), was then used to investigate the landing technique and patellar tendon loads generated during the landing phases of a stop-jump task by 16 male athletes with healthy patellar tendons (Chapter 4), and between seven male athletes with a PTA but with no previous history or clinical signs of patellar tendon injury who were then matched to seven male athletes with normal patellar tendons (Chapter 6). Part II and III used the experimental protocol that was developed in Part I (Chapter 3) to investigate the effect of fatigue on landing technique and patellar tendon loads generated during a stop-jump movement by 16 male athletes with normal patellar tendons (Chapter 5) and by seven asymptomatic athletes with a PTA (Chapter 7). During each stop-jump trial (Chapters 2, 4-7), the participants’ ground reaction forces (GRF) were recorded, three-dimensional kinematics estimated, and $F_{PT}$ calculated by dividing the net knee joint moment by the patellar tendon moment arm.

MAJOR CONCLUSIONS

In characterising the patellar tendon loads generated during the landing phases of a stop-jump task, it was evident that athletes with normal patellar tendons were able to reduce their patellar tendon loads when fatigued. This was achieved by altering their landing technique in a way which may have a protective effect and potentially decrease the likelihood of patellar tendon pathologies in vulnerable athletes. In contrast, asymptomatic athletes with a PTA utilised a different lower limb landing technique than their healthy counterparts with normal patellar tendons, by landing with greater knee flexion and utilising a hip extension rather than a hip flexion strategy. These asymptomatic athletes with a PTA, however, were unable to modify either their patellar
tendon load or their landing technique in response to fatigue. It was speculated that these asymptomatic athletes with a PTA, may be less able to adapt to changes evoked by fatigue and are therefore at risk of developing patellar tendinopathy due to higher patellar tendon loading.
# Table of Contents

<table>
<thead>
<tr>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedication.................................................................................................................................</td>
</tr>
<tr>
<td>Declaration.................................................................................................................................</td>
</tr>
<tr>
<td>Publications..............................................................................................................................</td>
</tr>
<tr>
<td>Acknowledgements.....................................................................................................................</td>
</tr>
<tr>
<td>Abstract..........................................................................................................................................</td>
</tr>
<tr>
<td>Table of Contents.......................................................................................................................</td>
</tr>
<tr>
<td>List of Tables...............................................................................................................................</td>
</tr>
<tr>
<td>List of Figures.............................................................................................................................</td>
</tr>
</tbody>
</table>

Chapter 1  
The Problem........................................................................................................................... 1  
INTRODUCTION......................................................................................................................... 1  
STATEMENT OF THE PROBLEM.................................................................................................. 5  
REFERENCES................................................................................................................................. 8

PART I  
Establishing a Valid and Reliable Experimental Protocol......................................................... 18

Chapter 2  
Lower Limb Symmetry Cannot be Assumed when Investigating the Biomechanics of a Stop-Jump Landing: Implications for Experimental Design.................................................................................. 19  
ABSTRACT...................................................................................................................................... 19  
INTRODUCTION........................................................................................................................... 20  
METHODS...................................................................................................................................... 20

  Participants................................................................................................................................. 22
  Experiment Task........................................................................................................................... 22
  Experimental Procedure.............................................................................................................. 23
  Data Reduction........................................................................................................................... 25
  Data Analysis.............................................................................................................................. 25
  Statistical Analysis..................................................................................................................... 26

RESULTS.......................................................................................................................................... 27

  Patellar Tendon Loading and Ground Reaction Forces.......................................................... 27
  Joint Kinematics.......................................................................................................................... 27
  Muscle Activation Patterns......................................................................................................... 30

DISCUSSION.................................................................................................................................... 32  
CONCLUSION................................................................................................................................. 34  
REFERENCES................................................................................................................................. 35

Chapter 3  
Reliability and Validity of a Lower Limb Stretch-Shortening Cycle Fatigue Protocol................. 41  
ABSTRACT...................................................................................................................................... 41  
INTRODUCTION........................................................................................................................... 42  
METHODS...................................................................................................................................... 44

  Participants................................................................................................................................. 44
  Experimental Protocol................................................................................................................... 45
  Stretch-Shortening Cycle Exercises.......................................................................................... 45
  Fatigue Protocol........................................................................................................................... 47
  Data Collection............................................................................................................................. 48
  Data Analysis............................................................................................................................... 48
PART II  Patellar Tendon Loading of Athletes with a Patellar Tendon Abnormality and How this is Moderated by Fatigue .................................................. 112

Chapter 6  Landing Strategies of Athletes with an Asymptomatic Patellar Tendon Abnormality ............................................................. 113
ABSTRACT ................................................................................................. 113
INTRODUCTION ....................................................................................... 114
METHODS .................................................................................................. 116
   Participants ............................................................................................ 116
   Experimental Task ................................................................................ 117
   Experimental Procedure ....................................................................... 118
   Data Reduction ..................................................................................... 119
   Data Analysis ....................................................................................... 120
   Statistics Analysis .............................................................................. 121
RESULTS ................................................................................................... 121
   Patellar Tendon Loading ...................................................................... 121
   Ground Reaction Forces ...................................................................... 123
   Joint Kinematic Data ........................................................................... 123
   Muscle Activation Patterns .................................................................. 124
DISCUSSION ............................................................................................. 127
CONCLUSION .......................................................................................... 132
REFERENCES .......................................................................................... 133

Chapter 7  Asymptomatic athletes with a patellar tendon abnormality do not adapt when fatigued ................................................................. 139
ABSTRACT ............................................................................................... 139
INTRODUCTION ....................................................................................... 140
METHODS .................................................................................................. 142
   Participants ............................................................................................ 142
   Experimental Protocol ........................................................................ 142
   Experimental Task ................................................................................ 143
   Fatigue Protocol ................................................................................... 143
   Experimental Procedures ...................................................................... 144
   Data Reduction ..................................................................................... 145
   Data Analysis ....................................................................................... 146
   Statistical Analysis ............................................................................. 147
RESULTS ................................................................................................... 147
   Fatigue Variables ................................................................................ 147
   Patellar Tendon Loading & Ground Reaction Forces ......................... 148
   Joint Kinematic Data ........................................................................... 149
   Muscle Activation Patterns .................................................................. 150
DISCUSSION ............................................................................................. 152
CONCLUSION .......................................................................................... 154
REFERENCES .......................................................................................... 155

Chapter 8  Summary, Conclusions and Recommendations for Future Research .... 160
SUMMARY ............................................................................................... 160
CONCLUSIONS ......................................................................................... 164
RECOMMENDATIONS FOR FUTURE RESEARCH .................................... 164
List of Tables

Table 1. Fatigue protocol variables displayed by the 13 participants for each of the three test sessions. ................................................................. 50

Table 2. Fatigue protocol variables derived from the 100 log transformed data for the 13 participants during Test Sessions 1 v 2 and Test Sessions 2 v 3. ............................................................................................................. 51

Table 3. PTA measurements in PTA Participants........................................... 117

Table 4. Lower limb muscle recruitment order relative to the time of the peak patellar tendon force during the horizontal and vertical landing phases of a stop-jump task. ................................................................. 127
# List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Schematic representation of structure of this thesis to achieve thesis aim.</td>
<td>7</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Phases of the stop-jump task (A) horizontal landing, (B) two-foot jump vertically upwards to strike a ball, and (C) vertical landing phase.</td>
<td>23</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Mean (± SD) of the forces (normalised to body weight) generated during the horizontal and vertical landing phases of a stop-jump task by the dominant and non-dominant lower limbs of 16 male participants with healthy patellar tendons.</td>
<td>28</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Mean (± SD) joint angles (°) displayed during the horizontal and vertical landing phases of a stop-jump task for the dominant and non-dominant lower limbs of 16 male participants with healthy patellar tendons.</td>
<td>29</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Mean (± SD) joint velocities (°.s⁻¹) generated during the horizontal and vertical landing phases of a stop-jump task by the dominant and non-dominant lower limbs of 16 male participants with healthy patellar tendons.</td>
<td>30</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Mean (± SD) for the times of the (A) onset of muscle activation and (B) the peak muscle activity relative to the time of the peak patellar tendon force (F&lt;sub&gt;PT&lt;/sub&gt;) generated during the horizontal and vertical landing phases of a stop-jump movement by the dominant and non-dominant lower limbs of 16 male participants with healthy patellar tendons.</td>
<td>31</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Flow chart illustrating the experimental protocol.</td>
<td>46</td>
</tr>
<tr>
<td>Figure 8</td>
<td>The five phases of the stop-jump movement identified from the vertical ground reaction force-time curve include: (1) preparation for the horizontal landing; (2) the first horizontal landing phase; (3) preparation for the take-off of the vertical jump; (4) preparation for the vertical landing; and (5) the vertical landing phase.</td>
<td>69</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Mean (± SD) of the forces generated during the horizontal and vertical landing phases of a stop-jump movement (normalised to body weight) of 16 male participants with healthy patellar tendons.</td>
<td>70</td>
</tr>
</tbody>
</table>
Figure 10. Representative data for the ankle, knee and hip joint angles (°), and the patellar tendon and ground reaction forces (BW) for a single participant with healthy patellar tendons during the horizontal and vertical landing phases of a stop-jump task. ............................................. 71

Figure 11. Mean (± SD) joint angles (°) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force (Fv) and at the time of the peak patellar tendon force (FPT) during the two landing phases of the stop-jump task of 16 male participants with healthy patellar tendons. .............................................................. 72

Figure 12. Mean (± SD) joint velocities (°.s⁻¹) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force (Fv) and at the time of the peak patellar tendon force (FPT) during the two landing phases of the stop-jump task of 16 male participants with healthy patellar tendons.......................... 73

Figure 13. Lower limb alignment during the horizontal and vertical landing phases of a stop-jump movement at initial foot-ground contact (IC) and at the time of the peak patellar tendon force (FPT). ..................... 74

Figure 14. Flow chart illustrating the experimental protocol. .......................................................... 91

Figure 15. Mean (± SD) of the forces generated during the horizontal and vertical landing phases of a stop-jump task (normalised to body weight) of athletes of 16 male participants with healthy patellar tendons.. .............. 96

Figure 16. Means (± SD) of joint angles (°) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force (Fv) and at the time of the peak patellar tendon force (FPT) during the two landing phases of the stop-jump task during the non-fatigued (NF) and fatigued (F) conditions of 16 male participants with healthy patellar tendons. .............................................................. 98

Figure 17. Means (± SD) of joint velocities (°.s⁻¹) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force (Fv) and at the time of the peak patellar tendon force (FPT) during the two landing phases of the stop-jump task of 16 male participants with healthy patellar tendons............................................................... 99
Figure 18. Means (± SD) for the times of the (A) onset of muscle activity relative to the time of the $F_{PT}$, represented as Time 0, and (B) Peak muscle activity relative to the time of the $F_{PT}$, represented as Time 0, during the two landing phases of the stop-jump task. .......................................................... 101

Figure 19. Mean (SD) values of the peak patellar tendon forces and the peak vertical ground reaction forces (normalised to body weight) generated by the PTA group and the controls during (1) the horizontal and (2) the vertical landing phases of a stop-jump task. .......................................................... 122

Figure 20. Means (SD) values of joint angles (°) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force ($F_V$) and at the time of the peak patellar tendon force ($F_{PT}$) during the two landing phases of the stop-jump task for the PTA and control groups. ......................................................................................... 124

Figure 21. Means (SD) values of joint velocities (°.s⁻¹) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force ($F_V$) and at the time of the peak patellar tendon force ($F_{PT}$) during the two landing phases of the stop-jump task for the PTA and control groups. ......................................................................................... 125

Figure 22. Means (SD) values for the times of (1) the onset of muscle activation and (2) the peak muscle activity relative to the time of the peak patellar tendon force ($F_{PT}$) generated during the horizontal (H) and vertical (V) landing phases of a stop-jump task for the PTA and control groups. ......................................................................................... 126

Figure 23. Mean (± SD) of the forces generated during the horizontal and vertical landing phases of a stop-jump task (normalised to body weight) of 7 asymptomatic male athletes with a PTA ................................................................. 148

Figure 24. Means (± SD) of joint angles (°) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force ($F_V$) and at the time of the peak patellar tendon force ($F_{PT}$) during the two landing phases of the stop-jump task of 7 asymptomatic male participants with a PTA ......................................................................................... 149

Figure 25. Means (± SD) of joint velocities (°.s⁻¹) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force
(Fv) and at the time of the peak patellar tendon force (FPT) during the two landing phases of the stop-jump task of 7 asymptomatic male participants with a PTA.

**Figure 26.** Mean (± SD) for the times of the (A) onset of muscle activation and (B) the peak muscle activity relative to the time of the peak patellar tendon force (FPT) generated during the horizontal and vertical landing phases of a stop-jump movement during the non-fatigued and fatigued condition of 7 asymptomatic male participants with a PTA.
Chapter 1

The Problem

INTRODUCTION

Patellar tendinopathy is a insidious overuse knee injury with a reported prevalence ranging from 10% to 45% (1-3) in sports involving repetitive jumping and landing, such as volleyball (1-3), basketball (2-4) and soccer (2,3). This is a complex condition that is difficult to treat (5), rest does not alleviate pain, and it can severely limit or potentially end an athletic career (6). Within the literature patellar tendinopathy has been described using a myriad of different terminology including jumper’s knee and patellar tendinitis. Advances in our understanding of this injury, however, indicate that the condition is not caused by an inflammatory process but rather from degeneration of the patellar tendon (7-12). The correct label is therefore patellar tendinopathy (9-16) and this label will be used to describe this overuse injury of the patellar tendon from here onwards.

In an attempt to provide a basis for prevention and treatment of patellar tendinopathy, research has investigated the numerous intrinsic and extrinsic risk factors thought to be associated with this overuse knee injury. An overview of these risk factors and their implications for rehabilitation programs has been presented by Crossley et al. (13) and Kountouris & Cook et al. (17). Although a wide range of intrinsic risk factors has been investigated to provide a more scientific basis for rehabilitation of patellar tendinopathy (13), many of these intrinsic risk factors are not readily moderated. Therefore, emphasis within this thesis is focused on extrinsic factors, which arise from outside the body and can be more easily modified.
One of the major extrinsic risk factors in the development of patellar tendinopathy is thought to be repetitive landing (18-22). As the structure, composition, and mechanical properties of tendons can be altered in response to mechanical loading (23), the patellar tendon will display histological adaptation in reaction to loading (24). For example, as patellar tendinopathy is an insertional tendinopathy in which the pathologic lesion is located at or near the insertion site of the tendon, known as the enthesis, adaptations will occur at the enthesis. An overview of the structure of the enthesis has been presented by Benjamin et al. (25,26) and the patellar tendon enthesis by Toumi et al. (27). However, as the patellar tendon sustains regional strain pattern variations, the stress-shielding side of the enthesis adapts to the compression loads, which leads to cartilage-like changes in the tendon (28). Nevertheless, such adaptations may reduce the ability of the tendon to withstand higher loads (28,29). Therefore, repetitive loading is the most frequently reported causative factor associated with patellar tendinopathy (13) and rehabilitation strategies have frequently focused on altering patellar tendon loading (6,30-35). As loading the patellar tendon at higher knee flexion angles increases stress-shielding and also potentially increases the compressive strain (36), lower limb landing techniques displayed by athletes may influence the development of patellar tendinopathy.

In order to identify factors that might contribute to high loading of the knee during repetitive landing tasks, research has investigated the biomechanics of lower limb landing techniques displayed by athletes with patellar tendinopathy while they perform vertical landing movements (19,37-39). This research has found that athletes with patellar tendinopathy alter their lower limb landing strategies relative to athletes without patellar tendinopathy (19,37-40), such as landing with greater knee flexion (19,38,39). These landing studies, however, have not quantified the patellar tendon
forces or knee joint loads generated by athletes with patellar tendinopathy during a dynamic landing task. Furthermore, no research has established the magnitude and/or loading patterns of the patellar tendon during a dynamic landing task of asymptomatic athletes with a normal patellar tendon against which comparisons can be made to athletes with patellar tendinopathy. Another limitation of these previous studies is that they have used a drop landing movement as the experimental task. The ecological validity of drop landing movements, however, is questionable, particularly in terms of whether drop landings simulate the landing phase of a whole jump-landing movement (41). Furthermore, drop landings are rarely performed in a sporting context. Ideally, a whole jump-landing task, such as the stop-jump movement, should be used to investigate patellar tendon loading during landing in an attempt to identify factors that might contribute to high and/or altered loading patterns of the patellar tendon and, in turn, patellar tendinopathy.

Fatigue is also thought to be a major risk factor in the development of knee joint injuries (42-45), particularly overuse injuries such as patellar tendinopathy, as a higher incidence of injuries occur towards the end of both halves (43) or in the later part of competitive team games (42,43). Lower limb fatigue may also contribute to patellar tendinopathy by altering the way an individual lands and, in turn, the magnitude and/or pattern of patellar tendon loading. Altered lower limb landing strategies have been observed both in healthy athletes as a consequence of being fatigued (44-46) and in athletes with patellar tendinopathy (19,37-40). It remains unknown, however, whether fatigue-induced alterations to an athlete’s lower limb landing technique lead to an increased risk of developing patellar tendinopathy in sports such as soccer, basketball or volleyball, which involve both repetitive landings and incur a high prevalence of patellar tendinopathy (2).
Although there has been extensive research into the effects of lower limb fatigue during landing tasks, conflicting results have been found regarding the effect of lower limb fatigue on landing technique (44,45). Fatigue during a landing task has been noted to increase (47,48), decrease (49-55) or not alter (48,56-60) the vertical ground reaction force generated during landing, as well as decrease (61) or not alter (44,53,62,63) the magnitude of knee flexion. Interpretation of between-study results are confounded by differences in experimental design, such as movement task (63,64) and/or fatigue protocol (63,65), as the mechanism of fatigue may vary according to the details of the task used to elicit fatigue (66-69). In order to systematically investigate the relationships among lower limb fatigue, landing technique, and knee joint injuries, a valid and reliable method of inducing lower limb fatigue needs to be developed.

One risk factor that could provide insight into the development of patellar tendinopathy, in terms of potentially altering an athlete’s lower limb landing technique and loading pattern of the patellar tendon, is the presence of a patellar tendon ultrasound abnormality on diagnostic imaging (PTA). A PTA is a hypoechoic region within the patellar tendon, as defined by Cook et al. (70), which indicates structural changes within the patellar tendon. Although a PTA and tendon pain are diagnostic criteria for patellar tendinopathy, a PTA can also be evident in athletes without tendon pain, with a prevalence of 22% to 32% (1,71-75). The likelihood of an asymptomatic athlete with a PTA developing patellar tendinopathy increases four times in basketball players (72) and 17% in elite soccer players compared to asymptomatic athletes with no evidence of a PTA (75). Despite being confirmed as a risk factor (70,72,75), a PTA can resolve, remain unchanged or worsen in athletes (73,75) without predicting symptoms of patellar tendinopathy (1,71,74).
Chapter 1: The Problem

Nevertheless, although altered lower limb landing strategies have been associated with patellar tendinopathy (19, 37-40), it remains unknown whether the development of a PTA is caused by a specific lower limb landing strategy that might contribute to the development of patellar tendinopathy via a high and/or altered loading patterns of the patellar tendon. Furthermore, it also remains unknown how lower limb fatigue affects the lower limb landing strategies in asymptomatic athletes with a PTA, and whether fatigue increases the risk of these athletes developing patellar tendinopathy.

STATEMENT OF THE PROBLEM

The primary purpose of this thesis was to systematically investigate and characterise the patellar tendon loading generated during dynamic landings, and the influence of fatigue and the presence of a patellar tendon abnormality on diagnostic imaging on these loads. To achieve this purpose, the thesis was completed in three parts. Part I aimed to establish valid and reliable experimental methods that could be used in Part II and III of this thesis to investigate the relationship among patellar tendon loading during dynamic landings, fatigue and the presence of a PTA. This involved firstly determining whether the experimental design could assume lower limb symmetry during a stop-jump landing (Chapter 2). The validity and reliability of an experimental protocol to induce lower limb fatigue was then established (Chapter 3).

The primary purpose of Part II of the thesis was to characterise the patellar tendon loads generated during a dynamic landing task by asymptomatic athletes with normal patellar tendon (Chapter 4), and to indicate how this was moderated by fatigue (Chapter 5). Part III then aimed to characterise the patellar tendon loads generated during a dynamic landing task by asymptomatic athletes with a PTA (Chapter 6), and to indicate how this was moderated by fatigue (Chapter 7). The summary of the
findings of the thesis, with recommendations for future research and clinical practice, are then summarised in Chapter 8. The way in which each of these chapters contributed to the overall aim of the thesis is depicted in Figure 1.
**Thesis Aim**

The primary purpose of this thesis was to systematically investigate and characterise the patellar tendon loading generated during dynamic landings, and the influence of fatigue and the presence of a patellar tendon abnormality on these loads.

---

**Part I**

Establishing the Experimental Protocol

- **Chapter 2**
  Lower limb symmetry cannot be assumed when investigating the biomechanics of a stop-jump landing: Implications for experimental design

- **Chapter 3**
  Reliability and validity of a lower limb stretch shortening cycle fatigue protocol

---

**Part II**

Characterising Patellar Tendon Loading of Athletes with Normal Patellar Tendons and How this is Moderated by Fatigue

- **Chapter 4**
  Characterising patellar tendon loads during the landing phases of a stop-jump movement

- **Chapter 5**
  Alterations to landing technique and patellar tendon loading in response to fatigue

---

**Part III**

Characterising Patellar Tendon Loading of Asymptomatic Athletes with a Patellar Tendon Abnormality and How this is Moderated by Fatigue

- **Chapter 6**
  Landing strategies of athletes with an asymptomatic patellar tendon abnormality

- **Chapter 7**
  Asymptomatic athletes with a patellar tendon abnormality do not adapt when fatigued

---

**Thesis Recommendations**

Summary on how patellar tendon loading is altered during dynamic landings and how this is moderated by fatigue and the presence of a patellar tendon abnormality. Provide important landing assessment criteria against which clinicians can identify athletes at possible risk of developing a patellar tendon abnormality and, in turn, patellar tendinopathy.

---

**Figure 1.** Schematic representation of structure of this thesis to achieve thesis aim.
REFERENCES


Chapter 1: The Problem


Chapter 1: The Problem


Chapter 1: The Problem


Part I

Establishing a Valid and Reliable

Experimental Protocol
Chapter 2

Lower Limb Symmetry Cannot be Assumed When Investigating the Biomechanics of a Stop-Jump Landing: Implications for Experimental Design

This chapter is an amended version of the manuscript: Edwards S, Steele JR, Cook JL, Purdam CR, McGhee DE. Lower limb symmetry cannot be assumed when investigating the biomechanics of a stop-jump landing: Implications for experimental design. Journal of Science and Medicine in Sport. Submitted for publication February, 2010.

ABSTRACT

When investigating lower limb landing biomechanics, researchers often assume movement symmetry for the simplicity of data collection and analysis, despite the fact that landing tasks often involve dual-limb motion. As it is unknown whether lower limb symmetry can be assumed when investigating dynamic, sport-specific movements such as the stop-jump, this study aimed to investigate whether there were any significant between-limb differences in selected kinetic, kinematic and muscle activation patterns characterising lower limb biomechanics of the landing phases of a stop-jump task. Sixteen male athletes with normal patellar tendons on diagnostic imaging performed five successful stop-jump trials. Patellar tendon forces, ground reaction forces, three-dimensional kinematics, and electromyographic activity of seven lower limb muscles were recorded for the dominant and non-dominant lower limb during each trial. Most biomechanical variables did not significantly vary as a function of lower limb dominance, implying relative lower limb symmetry throughout the landing phases of the stop-jump task. However, during the horizontal landing phase, the dominant lower limb
sustained a significantly higher peak patellar tendon force (F_{PT}), and a higher peak knee joint moment compared to the non-dominant lower limb. Furthermore, during the vertical landing phase, the dominant lower limb sustained significantly lower vertical but higher posterior ground reaction forces compared to non-dominant lower limb. It is recommended that researchers clearly identify their primary outcome variables and ensure their experimental design, particularly in terms of lower limb dominance, provides an appropriate framework to investigate possible mechanics underlying unilateral and bilateral knee joint injuries during dual-limb movements such as the stop-jump task.

**INTRODUCTION**

Researchers investigating the biomechanics of dual-limb landing tasks often assume movement symmetry (1,2) for the simplicity of data collection and analysis (1,3). However, whether this assumption is valid when analysing dynamic dual-limb landing tasks has not been established. Lower limb asymmetry is an important factor to consider as it can lead to preferential overloading of one lower limb (2), and, in turn, can contribute to the development of unilateral lower limb injuries, such patellar tendinopathy (4-6). Lower limb asymmetry can also place both limbs at an increased risk of a knee joint injury (7-9), as the dominant lower limb may sustain higher forces from its increased dependence and loading, whereas the weaker lower limb’s ability to tolerate typical forces may also be compromised (7). Furthermore, unilateral and bilateral patellar tendinopathy are thought to have different aetiologies (4,5), potentially indicating that these are distinct entities necessitating separate treatment (6). Therefore, lower limb symmetry in dual-limb landing tasks is an important experimental design consideration.
The biomechanics of dual-limb dynamic sporting movements, such as the stop-jump, have been extensively investigated in an attempt to identify potential risk factors associated with common knee joint injuries, such as patellar tendinopathy (10-16). The rationale for selecting tasks such as the stop-jump as the experimental movement is that these movements are repetitively performed in sports that have a high prevalence of patellar tendinopathy (17-20). Furthermore, stop-jumps are a common sporting skill performed in a variety of sports such as basketball, volleyball and soccer (12).

Previous researchers investigating lower limb landing mechanics of a stop-jump task have frequently collected and/or analysed data for only one lower limb, relying on the assumption of movement symmetry when interpreting the data. The limb tested during these dual-limbed stop-jump tasks has varied from the dominant lower limb, (12,15,16,21), the right lower limb (11,13,22) or has not been reported (10,14,23). Although movement symmetry has been investigated in drop landings (2,7,24), conflicting results have been reported due to different research designs and statistical analyses (2). The application of the results of these studies to knee injury mechanisms is also limited as drop landing tasks do not replicate game-like situations (25,26), and it is questionable whether they simulate the landing phase of a whole jump-landing movement (25). It remains unknown, therefore, whether lower limb symmetry can be assumed when investigating a dynamic, dual-limb sport-specific movement such as the stop-jump.

Given the paucity of research investigating lower limb symmetry during dynamic movements, this study aimed to investigate whether there was any significant between-limb differences in selected kinetic, kinematic and muscle activation patterns characterising lower limb biomechanics of the landing phases of a stop-jump task. We hypothesised that there would be significant differences in the biomechanical variables
characterising the dominant and non-dominant lower limb during the horizontal but not vertical landing phase of a stop-jump task. It was hypothesised that the dominant lower limb would sustain higher patellar tendon loading and a different lower limb landing strategy during the horizontal landing phase, but not the vertical landing phase of the stop-jump task compared to the non-dominant lower limb.

METHODS

Participants

Sixteen male basketball, soccer and volleyball athletes (mean age = 22.4 ± 2.9 years; height = 182.1 ± 8.7 cm; mass = 75.7 ± 10.1 kg), who reported no history of traumatic lower limb injuries were recruited. The patellar tendon morphology of all participants was documented as normal on diagnostic imaging by an experienced musculoskeletal radiologist using a 13 MHz linear array ultrasound transducer (Siemens Antares, Siemens AG, Germany). Written informed consent was obtained from each participant prior to data collection and all methods were conducted in accordance with the Institution’s Human Research Ethics Committee (HE06/205) requirements.

Experiment Task

The stop-jump task performed in this study involved two landing phases, a horizontal landing phase, immediately followed by a vertical landing phase (Figure 2). The horizontal landing phase required the participants to accelerate forwards for four steps towards two force platforms (mean (SD) approach speed 4.5 (0.4) m.s⁻¹ measured using infrared timing lights; OnSpot, University of Wollongong), to then jump off one lower limb and, to stop abruptly, performing a simultaneous two-foot landing with each foot contacting a separate force platform. Participants then immediately performed a two-foot jump vertically upwards to strike a ball, suspended from the ceiling, with both hands (mean (SD) vertical jump height 57 (5) cm). They then landed on both feet a
second time, with each foot again contacting a separate force platform simultaneously (vertical landing phase). During the stop-jump task familiarisation, the effort among the participants at which they performed the task was standardised by using a set starting position away from the force platform. Jump height effort was standardised among the participants by positioning the ball at the maximum height each participant could touch the ball with both hands after performing a stop-jump movement during task familiarisation.

![Figure 2](image)

**Figure 2.** Phases of the stop-jump task (A) horizontal landing, (B) two-foot jump vertically upwards to strike a ball, and (C) vertical landing phase.

**Experimental Procedure**

Each participant’s height, body mass, lower limb dimensions and ankle joint range of motion (27) were evaluated before determining their dominant lower limb, which was based on their preferred kicking leg (7). All participants were right leg dominant. After completing a 5-10 minute warm-up, each participant was then familiarised with the stop-jump task before performing approximately five successful stop-jump trials, whereby a successful trial was defined as a participant placing each foot wholly on a separate force platform during both landing phases and contacting the suspended ball with both hands. During each trial the ground reaction forces generated at landing were recorded (1000 Hz) using two multichannel force platforms (Type
9281B; Type 9253B; Kistler, Winterthur, Switzerland) embedded in the floor, with each platform connected to a multichannel charge amplifier (Type 9865A; Type, 9865B; Kistler, Winterthur, Switzerland). The participant’s three-dimensional lower limb motion was recorded (100 Hz) using an OPTOTRAK® 3020 motion analysis system (Northern Digital, Waterloo, Canada). Infrared light-emitting diodes were placed on each participant’s dominant lower limb and pelvis, on the shoe at the first and fifth metatarsal head and mid anterior foot, lateral and medial malleolus, lateral leg, anterior distal and anterior proximal leg, lateral and medial femoral epicondyle, lateral femur, anterior distal femur, anterior proximal femur, greater trochanter, anterior superior iliac spine and iliac crest. To avoid losing view of the infrared light-emitting diodes, the participants wore minimal clothing (a t-shirt and shorts). Socks and sports shoes were worn by the participants during the stop-jump.

Electromyographic activity was recorded bilaterally for vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), tibialis anterior (TA), and medial gastrocnemius (MG) using two Telemyo systems (Noraxon, Arizona, USA). Following standard preparation (28), bipolar silver-silver-chloride surface electrodes (Ambu® Blue Sensor M, electrode size = 40.8 x 32 mm, detection area = 13.2 mm) were placed longitudinally on each muscle belly (inter-electrode distance of 20 mm). A common reference electrode was located on the tibial tuberosity of each lower limb. The electromyographic signals for each lower limb were sampled (1000 Hz, bandwidth 16-500 Hz) and relayed from two TeleMyo 900 battery powered transmitters (Noraxon, Arizona, USA), firmly fixed around the participant’s waist, to two TeleMyo 900 receivers. The kinetic, kinematic and electromyographic data were time synchronised and collected using First Principles software (Version 1.00.2, Northern Digital, Waterloo, Canada).
Data Reduction

Analysis of the kinematic and kinetic data was performed using Visual 3D software (Version 3, C-Motion, Maryland, USA). The raw ground reaction force data were initially filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter \( f_c = 50 \) Hz before calculating the ground reaction force variables. The raw kinematic coordinates, ground reaction forces, free moments and center of pressure data were then filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter \( f_c = 18 \) Hz before calculating individual joint kinematics, internal knee joint moments and patellar tendon forces (24,29). The patellar tendon forces were calculated by dividing the net knee joint moment by the patellar tendon moment arm (30). Patellar tendon moment arms were calculated as a function of knee joint angle using the method of Herzog and Read (30).

The raw electromyographic signals were filtered using a fourth-order zero-phase shift Butterworth (high-pass \( f_c = 15 \) Hz) to eliminate any movement artefact. To quantify temporal characteristics of the muscle bursts, the filtered electromyographic data were full-wave rectified, filtered with a 20 Hz low pass filter and then full-wave rectified to create linear envelopes that were then screened using a threshold detector (8% of the maximum amplitude) (31) via custom software (LabVIEW 8, National Instruments, Austin, Texas, USA). Each individual muscle’s filtered signal was visually inspected to confirm the validity of the calculated results of the temporal characteristics of the muscle bursts to minimise the probability of error.

Data Analysis

The jump height attained by each participant during the stop-jump movement was defined as the difference in the maximum vertical displacement of the greater trochanter marker minus the vertical displacement of the same marker measured while
each participant stood motionless. The two landing phases within the stop-jump movement were then identified from the vertical ground reaction force-time curve as (i) the “horizontal” landing phase and (ii) the “vertical” landing phase. The primary outcome variable analysed during these two landing phases was the peak patellar tendon force ($F_{PT}$). Secondary variables analysed during the same two landing phases included the peak vertical ground reaction force ($F_V$); peak anterior-posterior ground reaction force ($F_{AP}$); ankle, knee and hip joint kinematics; and the time of the onset and peak muscle activity of each of the seven lower limb muscles relative to the time of the $F_{PT}$ in each landing phase. Loading rate of the $F_V$ (LR $F_V$, BW.s$^{-1}$) was calculated by dividing the $F_V$ by the time interval between IC to the time of the $F_V$. Loading rate of the $F_{PT}$ (LR $F_{PT}$, BW.s$^{-1}$) was calculated by dividing the $F_{PT}$ by the time interval between IC to the time of the $F_{PT}$. The temporal events (IC, and at the time of the peak $F_V$ and $F_{AP}$) were defined using the 18 Hz filtered kinetic data, with initial contact defined when the ground reaction force exceeded 30 N.

**Statistical Analysis**

Means and standard deviations were calculated for each kinetic, kinematic and muscle activity outcome variable for the participants’ dominant and non-dominant lower limbs during the horizontal and vertical landing phases of the stop-jump task. After confirming normality and equal variance, the data were analysed using a series of paired $t$-tests to determine whether there were any significant differences ($p < 0.05$) in the variables when comparing the dominant and non-dominant lower limb data. It was assumed that limb symmetry was evident when no statistically significant between-limb difference was identified. Although multiple statistical tests were conducted, increasing the chance of incurring an error, no adjustment to the alpha level was deemed necessary given the exploratory nature of the study and the low cost associated with incurring a
Type I error. All statistical procedures were conducted using SPSS Statistical Software (Version 15, SPSS Inc., Chicago, USA).

RESULTS

Patellar Tendon Loading and Ground Reaction Forces

During the horizontal landing phase, the participants’ dominant lower limb generated a significantly higher $F_{PT}$ ($p = 0.016$) and peak net knee joint extension moment ($p = 0.02$) relative to their non-dominant lower limb, although the $F_V$ and $F_{AP}$ were symmetrical. In contrast, during the vertical landing phase, the patellar tendon loading and the ground reaction forces were symmetrical (Figure 3). During both landing phases, participants displayed symmetry in timing of their foot placement in that both lower limbs contacted the ground at the same time (negative value indicates the right lower limb contacted the ground first; horizontal landing phase $= -10 \pm 18$ ms; vertical landing phase $= -11 \pm 21$ ms).

Joint Kinematics

Most of the lower limb kinematic variables analysed during the horizontal and vertical landing phases of the stop-jump task did not differ significantly between the participants’ dominant and non-dominant lower limbs (Figure 4 and Figure 5). However, knee joint asymmetries were evident during both landing phases, whereby the participants displayed significantly less knee flexion at IC ($p = 0.039$), and greater knee external rotation during the entire landing phase from IC ($p = 0.047$) to the times of the $F_V$ ($p < 0.01$) and the $F_{PT}$ ($p = 0.027$) when landing on their dominant lower limb compared to their non-dominant lower limb (Figure 4). Furthermore, the dominant lower limb displayed significantly increased forefoot abduction velocity at the time of the $F_V$ ($p = 0.042$), and increased ankle dorsiflexion velocity ($p = 0.035$) and tibial
Horizontal Landing

Vertical Landing

**Figure 3.** Mean (± SD) of the forces (normalised to body weight) generated during the horizontal and vertical landing phases of a stop-jump task by the dominant and non-dominant lower limbs of 16 male participants with healthy patellar tendons. (A) Peak vertical ground reaction force ($F_V$), peak anterior-posterior ground reaction force ($F_{AP}$), peak patellar tendon forces ($F_{PT}$) and peak net knee joint extension moment. (B) The loading rate of the $F_V$ (LR $F_V$) and the loading rate of the $F_{PT}$ (LR $F_{PT}$). (C) The time from initial foot-ground contact (IC) to the time of the $F_V$ (IC to $F_V$), the time from IC to the time of the $F_{AP}$ (IC to $F_{AP}$) and the time from IC to the time of the $F_{PT}$ (IC to $F_{PT}$). *Indicates a significant between-limb condition difference ($p < 0.05$).

Segment velocity (dominant = -335 ± 82; non-dominant = -283 ± 64; $p = 0.042$) at the time of the $F_{PT}$ during the horizontal landing phase when compared to the non-dominant lower limb. The dominant lower limb displayed a significantly greater forefoot abduction angle at the time of the $F_V$ ($p = 0.033$) during the vertical landing phase when...
Figure 4. Mean (± SD) joint angles (°) displayed during the horizontal and vertical landing phases of a stop-jump task for the dominant and non-dominant lower limbs of 16 male participants with healthy patellar tendons. *Indicates a significant between-limb difference ($p < 0.05$). IC, initial foot-ground contact; $F_V$, peak vertical ground reaction force; $F_{PT}$, peak patellar tendon force.

compared to the non-dominant lower limb.

Hip kinematics did not significantly differ between limbs throughout the entire horizontal landing phase. However, during the vertical landing phase, the participants displayed significantly less hip flexion at IC ($p = 0.013$) and at the time of the $F_V$ ($p < 0.001$), a slower hip flexion velocity at IC ($p = 0.018$), less hip abduction at IC ($p = 0.026$), and greater hip external rotation at the time of the $F_{PT}$ ($p = 0.023$) for the dominant lower limb relative to the non-dominant lower limb (Figure 5). Throughout
Figure 5. Mean (± SD) joint velocities (°·s⁻¹) generated during the horizontal and vertical landing phases of a stop-jump task by the dominant and non-dominant lower limbs of 16 male participants with healthy patellar tendons. *Indicates a significant between-limb difference (p < 0.05). IC, initial foot-ground contact; FV, peak vertical ground reaction force; FPT, peak patellar tendon force.

both landing phases and for both lower limbs, large variation was evident, particularly in the hip kinematic data, as reflected in the large standard deviations.

**Muscle Activation Patterns**

No significant between-limb differences were found in the muscle onsets or peak muscle burst activity relative to the time of the FPT during either landing phase (Figure 6).
Figure 6. Mean (± SD) for the times of the (A) onset of muscle activation and (B) the peak muscle activity relative to the time of the peak patellar tendon force (FPT) generated during the horizontal and vertical landing phases of a stop-jump movement by the dominant and non-dominant lower limbs of 16 male participants with healthy patellar tendons. Negative values indicate muscle activation variable occurred before FPT; VL = vastus lateralis; RF = rectus femoris; VM = vastus medialis; ST = semitendinosus; BF = biceps femoris; MG = medial gastrocnemius; TA = tibialis anterior.
DISCUSSION

Lower limb symmetry was observed in most of the kinetic, kinematic and muscle activation data during both the horizontal and vertical landing phases of the stop-jump task, and partially supports this study’s hypothesis. These finding are consistent with previous research which has investigated a vertical landing task and reported movement symmetry (24), although they are in contrast to others who have reported movement asymmetry (7). Where statistical significant differences in lower limb kinematics were found in the present study, the magnitude of the absolute differences was often functionally irrelevant (for example, a mean difference of 1.7° for knee flexion at IC during the vertical landing phase) or the mean differences were accompanied by large variation in the data (for example, hip kinematics). These results imply that the lower limb kinematics displayed by participants during the landing phases of a stop jump task in the present study were relatively symmetrical. There were several significant between-limb differences, however, in the kinetic and kinematic variables that are important to consider in experimental design, as discussed below.

During the horizontal landing phase the participants generated a significantly higher $F_{PT}$ for their dominant lower limb relative to their non-dominant lower limb supporting this study’s hypothesis. This between-limb difference in $F_{PT}$ was due to the dominant lower limb displaying a significantly higher peak knee joint moment and less knee flexion, which would lead to a smaller patellar tendon moment arm (30). We speculate that the higher knee joint moment was due to combination of factors including strong trends for a higher $F_V$ and $F_{AP}$, a faster knee joint velocity at the times of the $F_V$ and $F_{PT}$, and the significantly faster tibial segment velocity at the time of the $F_{PT}$ noted for the dominant lower limb relative to its non-dominant counterpart.
This asymmetrical patellar tendon loading noted during the horizontal landing phase suggests that in studies where the magnitude of the patellar force is a primary outcome variable, the participants’ dominant lower limbs should be tested. Furthermore, as excessive patellar tendon loading is a risk factor for patellar tendinopathy (32-38), future research investigating the biomechanics of knee joint injuries in horizontal landings should not assume lower limb symmetry and should investigate whether lower limb asymmetry increases the risk of an athlete sustaining a knee joint injury.

Interestingly, the asymmetry noted in the $F_{PT}$ during the horizontal landing phase was not evident during the vertical landing phase of the stop-jump task supporting this study’s hypothesis. This result suggests that when investigating vertical landings kinetics either lower limb could be tested, although the relevance of using vertical jumping tasks to investigate mechanics of knee injuries such as patellar tendinopathy is questionable (25).

It is noted that there were some significant differences in the kinematics of the lower limb, in particular knee rotation during both landing phases and hip flexion during the vertical landing phase. Therefore, researchers investigating joint kinematics during dynamic landing tasks are encouraged to account for between-limb differences in their experimental design.

The preparatory muscle activation strategy found during the horizontal and vertical landing phases of the stop-jump task was consistent with previous research (23). Although no between-limb differences in muscle onsets or peak muscle burst activity relative to the time of the $F_{PT}$ were found, high variability was evident in all the data, which was consistent with previous landing studies (25,39). This reflects the individual muscle recruitment strategies of the participants.
We acknowledge that there are limitations in the current experimental design. The two-dimensional model used to estimate patellar tendon force has limitations in that it will underestimate the patellar tendon force because it uses the net knee joint moment to estimate patellar tendon force. This calculation does not account for the flexor moment produced by the hamstring or gastrocnemius muscles, which must be compensated for by a higher knee extensor moment (40), or the different anthropometry of each participant’s patellar tendon moment arm, which was not scaled. It has been suggested that the patellar tendon should be modeled three-dimensionally due to its orientation in the sagittal and coronal planes. However, only two-dimensional linear regression equations exist for the patellar tendon (30,41), and these methods do not scale the moment arm according to the participant’s anthropometry. Furthermore, if the patellar tendon is modelled as a solid structure to estimate stresses and strains, regional strain pattern variations within the patellar tendon will be evident (42). These limitations should be addressed by developing a three-dimensional patellar tendon model with regional variations in stress that can be implemented in future studies to confirm our findings.

CONCLUSIONS

Most biomechanical variables characterising landing technique in this present study did not significantly vary as a function of lower limb dominance, implying relative lower limb symmetry throughout the landing phases of the stop-jump task. Nevertheless, as significant lower limb asymmetry was displayed for some important kinetic and kinematic variables that have been associated with knee joint injuries during landing tasks, it is recommended that researchers clearly identify their primary outcome variables, and ensure that their experimental design accounts for any possible effect of limb dominance. This will ensure their experimental design, particularly in terms of
lower limb dominance, provides an appropriate framework to investigate possible mechanics underlying unilateral and bilateral knee joint injuries during dynamic landing tasks such as the stop-jump task.

REFERENCES


15. Yu B, Herman D, Preston J, Lu W, Kirkendall DT, & Garrett WE. Immediate effects of a knee brace with a constraint to knee extension on knee kinematics


30. Herzog W, & Read LJ. Lines of action and moment arms of the major force- 
   carrying structures crossing the human knee joint. *Journal of Anatomy*. 1993: 

31. Cowling E, & Steele JR. Is lower limb muscle synchrony during landing 
   affected by gender? Implications for variations in ACL injury rates. *Journal of 

32. Cook JL, Khan KM, Kiss ZS, & Griffiths L. Patellar tendinopathy in junior 
   basketball players: a controlled clinical and ultrasonographic study of 268 
   patellar tendons in players aged 14-18 years. *Scandinavian Journal of Medicine 

   predict patellar tendinitis in elite volleyball players. *American Journal of Sports 

   295.


36. Lian O, Engebretsen L, Ovrebø RV, & Bahr R. Characteristics of the leg 
   extensors in male volleyball players with jumper's knee. *American Journal of 

37. Roels J, Martens M, Mulier JC, & Burssens A. Patellar tendinitis (jumper's 
Part I: Chapter 2


Chapter 3

Reliability and Validity of a Lower Limb Stretch-Shortening Cycle Fatigue Protocol

This chapter is an amended version of the manuscript: Edwards S, Steele JR, McGhee DE, Cook JL, Purdam CR. Reliability and validity of a lower limb stretch-shortening cycle fatigue protocol. Medicine & Science in Sports & Exercise. Submitted for publication February, 2010.

ABSTRACT

Purpose

As fatigued muscles are less able to absorb the loads generated during landing, it is thought that fatigue may contribute to the development of knee joint injuries by altering/decreasing muscle control of the knee during landing. This study aimed to develop a valid and reliable method to induce lower limb fatigue, which could be used in future research investigating the relationships among fatigue, landings and knee injuries.

Methods

Thirteen male athletes performed the experimental protocol on three occasions. The participants performed sets of 30 submaximal stretch-shortening cycle efforts immediately followed by 30 seconds rest during which the participants’ kinetics and kinematics were quantified and blood lactate samples recorded. Reliability was assessed from the percentage change in the mean, typical error of measurement (TEM) and test-retest correlation using 100log transformed data of each variable for consecutive pairs of test sessions.
Results

Maximal rebound height, number of sets and maximum knee joint angle for Test Sessions 2 to 3 showed a decrease in the TEM, good test-retest reliability, and a decrease or unchanged percentage change in the mean compared to Test Sessions 1 to 2. However, when comparing Test Sessions 2 to 3 to Test Sessions 1 to 2 for post-fatigue blood lactate level, TEM increased and test-retest reliability remained poor, although the percentage change in the mean decreased.

Conclusions

The critical factor to ensure reliability when inducing lower limb fatigue utilising the SSC muscle action characteristic of dynamic jumping/landing movements is to ensure participants complete a full familiarisation session to a fatigued state before data are collected. The fatigue protocol provides future researchers with a sport-appropriate method to investigate the relationships among fatigue, dynamic landings and knee joint injuries.

INTRODUCTION

Lower limb fatigue has been associated with an increased risk of knee joint injuries (1,2), with higher injury rates occurring towards the end of team sport matches (3,4). In sports involving repeated jumping and landing movements, it is thought that fatigue has the potential to alter the way athletes land, and in turn modify knee joint forces (1,5), because fatigued muscles are thought to have less ability to absorb the loads generated during jumping and landing tasks (6). However, conflicting results have been found regarding the effects of lower limb fatigue on landing technique (1,2), with interpretation of these between-study results confounded by task dependency, in which the mechanism of fatigue may vary according to the details of the task used to elicit fatigue (7-10). For example, the ground reaction forces generated during landing
have been shown to increase (11), decrease (12,13) or remain unaltered (14-16), as a consequence of fatigue. In order to systematically investigate the relationships between lower limb fatigue, landing technique, and knee joint injuries, a valid and reliable method of inducing lower limb fatigue needs to be developed.

A fatigue protocol requiring repeated use of the stretch-shortening cycle (SSC) offers an ideal model to investigate lower limb fatigue (17,18) as the SSC muscle action is characteristic of running (18,19), and jumping and landing (14,18,19) movements. Numerous researchers have utilised a SSC model to elicit lower limb fatigue, typically requiring subjects to perform a series of bilateral rebound jumps along the gliding track of a sledge apparatus (6,19-28). Many of these studies, however, have been limited in terms of both reliability and validity of the protocol used to elicit fatigue.

Although SSC fatigue protocols have been shown to result in high response variability and large inter-individual variation in the number of SSC exercises performed (26,27), the reliability of these protocols has not been reported. Furthermore, the validity of previous SSC fatigue protocols has been limited in terms of the range of lower limb motion, muscle length and rest intervals tested relative to those typically displayed during dynamic landing tasks in game-like scenarios. For example, during the landing phase of a stop-jump task, athletes typically land with a maximum knee angle of 65° and hip flexion angle of 49° (29). This is substantially less than the maximum knee (19,21,22,24,26) and/or hip (26,28) flexion angle used in previous SSC fatigue protocols. Furthermore, there have typically been no rest intervals incorporated within these protocols (6,19,20), which is inconsistent with the interval nature of most team sports.

In assessing the reliability of an experimental task, the typical error of measurement (TEM; calculated as a coefficient of variation percentage); the percentage
change in the mean; and the test-retest correlation (intraclass correlation; 2,1) can be used (30). The percentage change in the mean involves systemic error, such as the learning effect in which the participant benefits from the experience of the first trial by improving their performance of the second task compared to the first (30,31). In order to improve the reliability of the experimental task, it is important to reduce the learning effect by performing enough trials to minimise learning effects or other systematic changes before applying the intervention (30-32).

This study aimed to develop a valid and reliable method to induce lower limb fatigue utilising the SSC muscle action characteristic of dynamic jumping and landing movements. If achieved, this protocol could then be used in future research as a tool to investigate the relationship between lower limb fatigue, landing strategy and knee joint injuries. It was hypothesised that the method to induce lower limb fatigue utilising the SSC exercise would become more reliable between later test sessions than compared to between earlier test sessions.

**METHODS**

**Participants**

Thirteen skilled male basketball, soccer and volleyball athletes (mean age = 23.7 ± 4.0 years; height = 183.0 ± 6.2 cm; mass = 82 ± 10.4 kg) were recruited from team sports involving repetitive landing. All participants were right leg dominant, based on their preferred kicking leg (33). Participants reported no history of traumatic lower limb injuries and were injury-free at the time of testing. Written informed consent was obtained from each participant prior to data collection and all methods were conducted in accordance with the University of Wollongong Human Research Ethics Committee (HE03/066) requirements.
**Experimental Protocol**

To test reliability of the lower limb fatigue protocol, each participant performed the entire experimental protocol on three separate occasions (Test Sessions 1, 2 and 3) with at least 7 days between testing sessions to ensure sufficient recovery time. At each session the participants completed a 5-10 minute warm-up followed by a familiarisation with the SSC exercise on the sledge apparatus, and a pre-fatigue blood lactate test. The participants then performed three maximal SSC exercises (described below) to record their maximal rebound height and to calculate their submaximal rebound height followed by the fatigue protocol sets (described below). Immediately after the fatigue protocol sets were completed, a post-fatigue blood lactate test was recorded (Figure 7).

**Stretch-Shortening Cycle Exercises**

Participants performed the maximal and submaximal SSC exercises on a custom-built 23 kg sledge apparatus seat, which glided along a track inclined 23.6° from the horizontal (Figure 7). To ensure validity of the fatigue protocol, each participant was seated so their hip angle was set to 40° to replicate hip joint angles typically displayed during the landing phase of a stop-jump task (29).

For each maximal SSC exercise, the participants performed two submaximal SSC efforts, immediately followed by a maximal SSC effort. Each SSC effort required the participants to begin with their left and right feet contacting separate force platforms that were secured to the base frame of the sledge apparatus. From this starting position, the participants pushed off the force platforms and accelerated upwards along the gliding track of the sledge. For the maximal SSC efforts, maximal rebound height was required before returning down the track to stop in a two-foot landing with each foot again contacting separate force platforms, and flexing their knees to a maximum
Part I: Chapter 3

Figure 7. Flow chart illustrating the experimental protocol.

Warm-up

Familiarization of SSC exercise in the sledge apparatus

Pre-fatigue blood lactate test

3 x maximum SSC exercise to determine maximal rebound height

Fatigue Protocol

Repeated sets of 30 x submaximal SSC exercise to ≥70% of the maximal SSC exercise rebound height, with 30 s rest until no longer able to achieve ≥70% of the maximal SSC exercise rebound height for 3 out of 5 SSC exercises or until self-termination of the protocol

Post-fatigue blood lactate test
of approximately 75°. Although a higher maximal SSC rebound height could be attained if the participants flexed their knees to 90°, higher knee flexion angles are uncommon in landing tasks performed in game-like conditions (29). For the submaximal SSC efforts, the participants were required to achieve a submaximal rebound height of at least 70% of their maximal rebound height, before performing the symmetrical two-foot landing, again flexing their knees to a maximum of approximately 75°. To ensure participants met the criterion of the maximum knee flexion and 70% of their maximal SSC exercise rebound height during the SSC exercise, participants were given real-time verbal feedback from the investigator based on two marks which were set on the frame of the sledge apparatus that indicated that the participant had achieved each criterion.

**Fatigue Protocol**

The fatigue protocol involved participants repeatedly performing sets of 30 submaximal SSC efforts immediately followed by 30 seconds rest. The protocol continued until the participants were deemed to be fatigued when they could no longer reach 70% of their maximal SSC exercise rebound height for three out of five submaximal SSC exercises or the participants self-terminated the fatigue protocol as they felt that they could no longer continue. Participants were given verbal feedback and encouragement to assist in maintaining the predetermined rebound height and maximum knee flexion angle. An increase in blood lactate levels of at least 6 mmol/L was also used to confirm fatigue. Blood lactate was analysed using an Accusport blood lactate analyser (Boehringer Mannheim, Germany). Blood samples were taken from each participant’s fingertip at rest before testing and immediately following the fatigue protocol.
**Data Collection**

During each of the submaximal and maximal SSC efforts, the ground reaction forces generated at landing were recorded (1000 Hz) using two multichannel force platforms (Type 9281B; Type 9253B; Kistler, Winterthur, Switzerland) that were fixed to the sledge frame, perpendicular to the sliding track. Each force platform was connected to a multichannel charge amplifier (Type 9865A; Type, 9865B; Kistler, Winterthur, Switzerland). The participant’s three-dimensional lower limb motion during each SSC effort was recorded (100 Hz) using an OPTOTRAK® 3020 motion analysis system (Northern Digital, Waterloo, Canada). Infrared light-emitting diodes were placed on each participant’s lower limbs and pelvis at the fifth metatarsal head; lateral heel; lateral malleolus, lateral leg, anterior distal leg, fibula head, lateral femoral epicondyle, lateral femur, anterior distal femur, anterior proximal femur; greater trochanter and anterior superior iliac spine, and on each lateral side of the seat within the sledge apparatus. To avoid losing view of the infrared light-emitting diodes, the participants wore minimal clothing (a t-shirt, shorts and sports shoes). The kinetic and kinematic data were time synchronised and collected using ToolBench software (Version 3.00.34, Northern Digital, Waterloo, Canada).

**Data Analysis**

Analyses of the kinematic and kinetic data were performed using Visual 3D software (Version 3, C-Motion, Maryland, USA). The raw kinematic coordinates ($f_c = 8$ Hz) and the ground reaction forces ($f_c = 50$ Hz) were initially filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter. The rebound height attained by each participant during the submaximal and maximal SSC exercise efforts was defined as the difference in the maximum vertical displacement of the right seat marker.
minus the vertical displacement of the same marker measured while each participant was positioned in the sledge apparatus with 75º of knee flexion.

**Statistics**

Means and standard deviations were calculated for the maximal rebound height, the rebound height for the last five SCC exercise efforts in the final set, the maximum knee flexion angle for the middle 10 SSC exercise efforts in the midpoint set, the number of sets, and the pre- and post-fatigue blood lactate level. Due to the heteroscedasticity of the fatigue protocol data, the raw data were logarithmically transformed (30) using Microsoft Excel (34). Consecutive trial pairs of the transformed data (Test Session 1 and 2; Test Session 2 and 3) were then analysed to assess for any learning effect (30). Three measures were used to assess the reliability of the fatigue protocol: the typical error of measurement (TEM; calculated as a coefficient of variation percentage); the percentage change in the mean; and the test-retest correlation (intraclass correlation; 2,1) (30). The validity of the fatigue protocol to induce fatigue was assessed by the decrease of the submaximal rebound height of at least 70% of the maximal rebound height of the final set and an increase in blood lactate levels of at least 6 mmol/L. Paired t-tests were used to determine whether there was any significant ($p < 0.05$) difference between the pre- and post-fatigue blood lactate levels. The maximum knee flexion angle of the middle 10 SSC exercises during the midpoint set of the fatigue protocol was used to assess the validity of the SSC exercise to replicate a dynamic landing task typically displayed.

**RESULTS**

**Fatigue Criteria Variables**

Descriptive statistics for the maximal rebound height, number of sets/jumps, rebound height in the final set, maximum knee flexion angle in the midpoint set and
blood lactate levels following the fatigue protocol across the three test sessions are listed in Table 1.

**Table 1.** Fatigue protocol variables displayed by the 13 participants for each of the three test sessions*.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal rebound height (cm)</td>
<td>97.6 ± 11.3</td>
<td>97.8 ± 10.0</td>
<td>99.6 ± 10.0</td>
</tr>
<tr>
<td>Number of sets</td>
<td>12.8 ± 6.7</td>
<td>13.7 ± 5.6</td>
<td>13.8 ± 8.5</td>
</tr>
<tr>
<td>Number of jumps</td>
<td>385 ± 201</td>
<td>410 ± 167</td>
<td>413 ± 254</td>
</tr>
<tr>
<td>Rebound height of final set (as a percentage of maximal rebound height)</td>
<td>58 ± 10</td>
<td>61 ± 8</td>
<td>65 ± 7</td>
</tr>
<tr>
<td>Maximum knee flexion angle&lt;sup&gt;b&lt;/sup&gt; (°)</td>
<td>87 ± 13</td>
<td>78 ± 9</td>
<td>78 ± 9</td>
</tr>
<tr>
<td>Blood lactate (mmol.L&lt;sup&gt;-1&lt;/sup&gt;)</td>
<td>11.0 ± 2.8</td>
<td>8.9 ± 1.3</td>
<td>9.3 ± 3.5</td>
</tr>
</tbody>
</table>

<sup>a</sup>all values ± standard deviation.  
<sup>b</sup>Mean maximum knee angle of the middle 10 SSC exercises during the midpoint set of the fatigue protocol.

**Fatigue Protocol Reliability Variables**

Reliability of the fatigue protocol was assessed by the percentage change in the mean, the TEM, and the test-retest correlation (using the 100log transformed data) of the maximal rebound height, number of sets, the maximum knee flexion angle and the post-fatigue blood lactate level between Test Sessions 1 and 2 compared to that between Test Sessions 2 and 3 (Table 2). The maximal rebound height was found to be more reliable between Test Sessions 2 and 3 compared to Test Sessions 1 and 2 in terms of both the TEM and test-retest correlation, although this finding was not reflected in the percentage change in the mean. The number of sets was found to be more reliable between Test Sessions 2 and 3 compared to Test Sessions 1 and 2 in terms of the TEM, the percentage change in the mean and test-retest correlation. The rebound height in the final set in terms of the TEM and test-retest correlation remained unchanged between test sessions, although this finding was not reflected in terms of the percentage change data, which increased between Test Session 2 and 3 compared to Test Sessions 1 and 2.
The maximum knee flexion angle was found to be significantly more reliable between Test Sessions 2 and 3 compared to Test Sessions 1 and 2 in terms of both the TEM and test-retest correlation, although this finding was not reflected in terms of the percentage change data, which remained low and unchanged between test sessions. However, there was no change in the poor reliability of the blood lactate levels between Test Session 2 and 3 compared to Test Sessions 1 and 2 in terms of the TEM and test-retest correlation, although the percentage change decreased.

Table 2. Fatigue protocol variables derived from the 100log transformed data for the 13 participants during Test Sessions 1 v 2 and Test Sessions 2 v 3.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Test Session</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1 versus 2</td>
<td>2 versus 3</td>
<td></td>
</tr>
<tr>
<td>Maximal Rebound Height</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>11</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Change in mean (%)(^a)</td>
<td>0.4 (-5.9—7.1)</td>
<td>2.6 (-1.5—6.8)</td>
<td></td>
</tr>
<tr>
<td>Typical error mean(^b)</td>
<td>7.5 (5.2—13.0)</td>
<td>4.4 (3.0—7.8)</td>
<td></td>
</tr>
<tr>
<td>ICC(^c)</td>
<td>0.616</td>
<td>0.816</td>
<td></td>
</tr>
<tr>
<td>Number of Sets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>12</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Change in mean (%; 95% CI)</td>
<td>7.4 (-21.1—46.1)</td>
<td>-2.4 (-24.7—26.5)</td>
<td></td>
</tr>
<tr>
<td>Typical error mean (95% CI)</td>
<td>43.4 (29.5—91.3)</td>
<td>31.4 (21.0—61.5)</td>
<td></td>
</tr>
<tr>
<td>ICC(^c)</td>
<td>0.548</td>
<td>0.837</td>
<td></td>
</tr>
<tr>
<td>Rebound Height of Final Set(^d)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>10</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>Change in mean (%)</td>
<td>1.2 (-10.6—9.2)</td>
<td>4.7 (-4.7—14.9)</td>
<td></td>
</tr>
<tr>
<td>Typical error mean (95% CI)</td>
<td>10.4 (7.7—19.8)</td>
<td>9.0 (6.0—17.9)</td>
<td></td>
</tr>
<tr>
<td>ICC(^c)</td>
<td>0.308</td>
<td>0.424</td>
<td></td>
</tr>
<tr>
<td>Maximum Knee Angle(^e)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>10</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Change in mean (%)</td>
<td>-1.1 (-12.2—11.5)</td>
<td>-1.4 (-5.5—2.9)</td>
<td></td>
</tr>
<tr>
<td>Typical error mean (95% CI)</td>
<td>11.6 (7.7—23.4)</td>
<td>3.7 (2.4—7.6)</td>
<td></td>
</tr>
<tr>
<td>ICC(^c)</td>
<td>0.330</td>
<td>0.858</td>
<td></td>
</tr>
<tr>
<td>Blood Lactate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degrees of freedom</td>
<td>10</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td>Change in mean (%)</td>
<td>-20.5 (-33.3—-5.2)</td>
<td>-2.8 (-29.6—34.2)</td>
<td></td>
</tr>
<tr>
<td>Typical error mean (95% CI)</td>
<td>20.3 (14.7—34.3)</td>
<td>31.4 (21.3—63.4)</td>
<td></td>
</tr>
<tr>
<td>ICC(^c)</td>
<td>-0.263</td>
<td>0.169</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Change in mean as a percentage and the 95% confidence intervals.  
\(^b\)Typical error mean as a co-efficient of variation percentage.
\(^c\)Intraclass correlation (2,1).
\(^d\)Rebound height of the final set as a percentage of the maximal rebound height.
\(^e\)Mean maximum knee flexion angle of 10 SSC exercises during the middle set within the fatigue protocol.
DISCUSSION

Results of the present study support the hypothesis and have highlighted that the critical factor to ensure reliability when using the fatigue protocol, described in this study, as a tool to induce lower limb fatigue, is to ensure that participants complete a full familiarisation session of the entire fatigue protocol to a fatigued state and then recover before data are collected. The rationale for this finding is discussed below.

The number of jumps performed by participants during the fatigue protocol in the present study was both higher (6,19,20,24) and lower (26,27) than that reported by previous researchers who induced lower limb fatigue utilising a SSC exercise protocol in a sledge apparatus. These differences can be attributed to between-study differences in the fatigue protocol methods in terms of the rest intervals (6,19,20,26); angles of inclination of the sledge apparatus relative to the horizontal (6,19-26,35); maximum knee flexion angle during the contact phase on the force platform (19,21,22,24,26), and hip flexion angle (26,28).

The post-fatigue blood lactate levels in the present study were similar (6,19,20,27) or lower (22,24) to that reported in previous research. However, it should be noted that some of the participants in the present study did not meet the blood lactate level fatigue criteria because the true physiological peak (28) was missed due to either a delay in obtaining the post-fatigue blood lactate sample or fast recovery of the blood lactate level.

To confirm the validity of this current study’s SSC fatigue protocol relative to typical dynamic jumping and landing movements, the maximum knee joint angle displayed by each participant during the landing phase in the SSC exercise in the midpoint set was calculated. The results of this analysis indicated that, if a full familiarisation session of the fatigue protocol was completed, the participants were able
to reliably replicate the maximum knee flexion criteria, confirmed by a reduction in the TEM as well as good test-retest reliability between Test Sessions 2 and 3 compared to Test Sessions 1 and 2, and a low percentage change in the mean, which remained unchanged between test sessions. It should be noted that due to the explosive nature of the SSC exercise, some participants experienced difficulty in achieving this criterion as reflected in the standard deviation (Table 1), particularly during Test Session 1, but to a lesser extent during Test Session 2 and 3.

The maximal rebound height attained during the maximal SSC efforts defines the rebound height that each participant is required to attain during the fatigue protocol. Therefore, it is crucial that the maximal rebound height achieved is repeatable if the fatigue protocol is to be reliable. In the current study, the percentage change in the mean of the maximal rebound height values remained similar between test sessions, suggesting a similar amount of sampling error between test sessions and no systemic error. That is, there was no evidence of practice, learning, or other familiarisation effects on the maximal rebound height data. A slight reduction in the TEM occurred between Test Sessions 2 and 3 compared to Test Sessions 1 and 2, which may have been influenced by the range of participants recruited (32). Good test-retest reliability was established if the participants performed a familiarisation session of the fatigue protocol.

Reliability of the number of sets performed by the participants during the fatigue protocol was achieved but only if the participants performed a full familiarisation session of the fatigue protocol, whereby a reduction in the change in the mean in the number of sets performed indicated sampling and systematic errors due to practice effects without the familiarisation (30). This result suggests that the number of sets attained during the fatigue protocol was affected by factors such as change in skill level,
fitness motivation, fatigue or anxiety brought about by the previous fatigue protocol (30,32), and confirms that a familiarisation session of the fatigue protocol is required to ensure learning effects are negligible, and to reduce performance variability. Furthermore, a reduction in the TEM for the number of sets performed also occurred if the participants performed a familiarisation session of the fatigue protocol. Nevertheless, the TEM was very high between all fatigue protocols, which may indicate poor reliability in time-to-exhaustion exercise protocols (36). However, this high TEM is not unusual in exercise time-to-exhaustion protocols (34,36,37), and these protocols may still be sensitive to detecting exercise time-to-exhaustion performance changes as exercise time-to-exhaustion protocols can generally elicit large changes after an intervention (34). This high TEM may also be a consequence of fatigue, boredom and/or lack of motivation (34) and may have been influenced by the range of participants recruited, suggesting that variations in physical fitness, physical activity, training or diet may have contributed to the high variability in performance (32). Good test-retest reproducibility for the number of sets performed during the fatigue protocol was established if the participants performed a familiarisation session of the fatigue protocol prior to an intervention, confirming the importance of a fatigue protocol familiarisation to lead to an enhanced and consistent performance (38,39).

Although, the fatigue criteria was met in the Test Sessions (Table 1), there was no difference in the change of the mean or the TEM between Test Session 2 and 3 compared to Test Sessions 1 and 2, and a low test-retest reliability correlation across the fatigue protocols.

The validity of this current study’s SSC fatigue protocol to induce fatigue was confirmed by the decrease of the submaximal rebound height of at least 70% of the maximal rebound height of the final set and an increase in blood lactate levels of at least
Part I: Chapter 3

6 mmol/L (Table 1). Although participants fulfilled the fatigue criterion in terms of validity of this current fatigue protocol to induce fatigue, the rebound height of the final set and the blood lactate data displayed poor reliability. That is, the rebound height in the final set in terms of the TEM and test-retest correlation remained unchanged between test sessions. Although there was an increase in the percentage change data between Test Session 2 and 3 compared to Test Sessions 1 and 2, the 95% CI remained unchanged between test sessions. Furthermore, although the mean blood lactate showed a decrease in the change of the mean between Test Session 2 and 3 compared to Test Sessions 1 and 2, this result was confounded by an increase in TEM between Test Session 2 and 3 compared to Test Sessions 1 and 2 and a low test-retest reliability correlation across the fatigue protocols. This suggests that rebound height of the final set and the blood lactate values were poor indicators of the degree to which participants are fatigued in protocols involving repeated jumping and landing movements and should be used with caution as indicators to determine the level of fatigue attained. Irrespective of whether a participant performs a familiarisation session of the fatigue protocol prior to an intervention to negate a learning effect, rebound height of the final set or the blood lactate levels cannot be reliably replicated.

Consistent with previous research, participants displayed high response variability in terms of large inter-individual variations in the number of sets of SSC exercises performed (26,27). Differences in muscle structure have been suggested to contribute to this variability (27), causing two subgroups to exist: (i) “fast-exhaustive” participants, with more fast-twitch fibres, who perform a lower number of jumps, with greater power, and (ii) “slow exhaustive” participants, with more slow-twitch fibres, who perform a higher number of jumps, with greater endurance. The results of this study support this notion as some participants achieved a higher maximal rebound
height and a low number of jumps/sets, “fast-exhaustive”, whereas others achieved a lower maximal rebound height, with a higher number of jumps/sets, “slow-exhaustive”. Furthermore, even after a heterogeneous sample has been log transformed, participants at either end of the sample may still differ in their typical percentage error. Future research investigating this high variability in response could overcome this problem by dividing participants into groups such as fast- or slow-exhaustive groups (30).

CONCLUSION

The fatigue protocol described in this study utilising the SSC muscle action characteristic of dynamic jumping and landing movements, proved to be a reliable method to induce lower limb fatigue when a familiarisation session of the fatigue protocol was performed. This protocol provides researchers with a valid, reliable and a sport-appropriate method to systematically investigate the relationships among lower limb fatigue, landing technique and knee injuries.

REFERENCES


26. Regueme SC, Nicol C, Barthelemy J, & Grelot L. Acute and delayed neuromuscular adjustments of the triceps surae muscle group to exhaustive


Part II

Patellar Tendon Loading of Athletes

with Normal Patellar Tendons and

How this is Moderated by Fatigue
Chapter 4

Characterising Patellar Tendon Loads During the Landing Phases of a Stop-Jump Movement


ABSTRACT

Excessive extensor mechanism loading from repeated landing has been associated with overuse knee injuries, especially patellar tendinopathy. In order to reduce these loads, it is important to establish which landing task places the highest load on the patellar tendon. It was hypothesised that the horizontal landing would create higher patellar tendon force (F_{PT}) compared to the vertical landing. Sixteen male athletes with healthy patellar tendons performed five successful trials of a stop-jump task, which involved a simultaneous two-foot landing after a horizontal approach (horizontal landing) followed by another simultaneous two-foot landing after a vertical jump (vertical landing). For both lower limbs during each trial, the participants’ ground reaction forces were recorded, three-dimensional kinematics measured, and F_{PT} calculated by dividing the net knee joint moment by the patellar tendon moment arm. Compared to the vertical landing, significantly higher F_{PT}, posterior ground reaction forces and F_{PT} loading rates were generated during the horizontal landing, despite lower F_{V}, highlighting the notion that F_{V} should not be used to reflect F_{PT}. Understanding that a horizontal landing task places the highest load on the patellar tendon, provides an
appropriate framework for future research to investigate lower limb landing strategies in athletes with patellar tendinopathy.

**INTRODUCTION**

During sports involving repetitive jumping and landing, such as basketball, soccer and volleyball, athletes repeatedly place large loads on their knee extensor mechanism, including the patellar tendon. This repetitive landing is thought to be a major extrinsic risk factor in the development of patellar tendinopathy (1-5). Consequently, research into patellar tendinopathy has investigated the biomechanics of landing (2,6-8) in an attempt to identify factors that might contribute to high loading of the knee, in order to provide a basis for prevention and treatment of these overuse injuries. However, these studies have typically used the peak vertical ground reaction force generated during landing to represent the force sustained by the patellar tendon. Although high vertical ground reaction forces have been found to be a predictor of patellar tendinopathy (2), research investigating a squat and countermovement jump found that, although both movements involved similar peak vertical ground reaction forces, very different peak patellar tendon forces were generated during the two movements (9). These results imply that the peak vertical ground reaction force generated during landing may not accurately reflect the loads sustained by the patellar tendon.

Research investigating lower limb landing mechanics has typically focussed on vertical landings (2,7,8,10-14). Many of these landing studies, however, have used a drop landing movement as the experimental task and have extrapolated their results obtained during these drop jump movements to a variety of landing activities in sports (7,12,15). Drop landings, however, are rarely performed in a sporting context. Furthermore, it is questionable whether drop landings simulate the landing phase of a
jump-landing movement (38). Ideally, a whole jump-landing task, such as the stop-jump movement, should be used to investigate patellar tendon loading during landing. A stop-jump movement typically involves an athlete accelerating horizontally forward to then suddenly stop and perform a two-foot landing, immediately followed by jumping vertically upwards to perform a second two-foot landing. Despite being a commonly performed movement in sports that have high rates of patellar tendon injury, no studies were located that have quantified patellar tendon loading during the two landing phases of a stop-jump movement.

The purpose of this study was to quantify the patellar tendon loads generated by asymptomatic athletes with normal patellar tendons during the horizontal and vertical landing phases of the stop-jump movement. We hypothesised that athletes would sustain higher patellar tendon loading and display a different lower limb landing strategy during the horizontal landing phase compared to the vertical landing phase of the stop-jump movement.

**METHODS**

**Participants**

Sixteen skilled male basketball, soccer and volleyball athletes (mean age = 22.4 ± 2.9 years; height = 182.1 ± 8.7 cm; mass = 75.7 ± 10.1 kg) were recruited. All participants were right leg dominant, based on their preferred kicking leg (17). Participants reported no history of traumatic lower limb injuries. The patellar tendon morphology of all participants was documented as normal by an experienced musculoskeletal radiologist using a 13 MHz linear array ultrasound transducer (Siemens Antares, Siemens AG, Erlangen, Germany). Written informed consent was obtained from each participant prior to data collection and all the study’s methods were approved
by the review board of the University of Wollongong Human Research Ethics Committee (HE06/205).

**Experimental Task**

The stop-jump movement was chosen as the experimental task as this is a common sporting skill performed in basketball, volleyball and soccer (18), and is a frequently used movement task when investigating knee joint injuries (18-24). The stop-jump task performed in this study had a horizontal landing phase, immediately followed by a vertical landing phase. The horizontal landing phase required the participants to accelerate forwards for four steps towards two force platforms, to stop and perform a simultaneous two-foot landing with each foot contacting a separate force platform. The vertical landing phase immediately followed and required the participants to jump vertically upwards to strike a ball suspended from the ceiling and to then perform a simultaneous two-foot landing a second time with each foot again contacting a separate force platform. During the stop-jump task familiarisation, the effort among the participants at which they performed the task was standardised. To achieve this, a starting marker was placed on the laboratory floor to ensure that each participant accelerated forwards for exactly four steps toward the force platforms, to stop and perform a simultaneous two-foot landing with each foot contacting a separate force platform. The participants’ average approach speed was $4.5 \pm 0.4$ m/s, measured immediately before the preparation phase of the horizontal landing phase, using infrared timing lights (OnSpot, University of Wollongong). Jump height effort was standardised among the participants by positioning the ball at the maximum height each participant could touch the ball with both hands before the preparation phase of the horizontal landing phase. The average vertical jump height attained by the participants was $57 \pm 5$
cm. Before performing the stop-jump movement, each participant’s height, body mass, lower limb dimensions and ankle joint range of motion (25) were evaluated.

**Experimental Procedure**

After completing a 5-10 minute warm-up, each participant was familiarised with the stop-jump task before performing approximately 10 stop-jump trials. During each trial the ground reaction forces generated at landing were recorded (1000 Hz) using two multichannel force platforms (Type 9281B; Type 9253B; Kistler, Winterthur, Switzerland) embedded in the floor, with each platform connected to a multichannel charge amplifier (Type 9865A; Type, 9865B; Kistler, Winterthur, Switzerland). The participant’s three-dimensional lower limb motion was recorded (100 Hz) using an OPTOTRAK® 3020 motion analysis system (Northern Digital, Waterloo, Ontario, Canada). Infrared light-emitting diodes were placed on each participant’s dominant lower limb and pelvis at the first and fifth metatarsal head; mid anterior foot; lateral and medial malleolus, lateral leg, anterior distal and anterior proximal leg, lateral and medial femoral epicondyle, lateral femur, anterior distal femur, anterior proximal femur; greater trochanter, anterior superior iliac spine and iliac crest. To avoid losing view of the infrared light-emitting diodes, the participants wore minimal clothing (a t-shirt and shorts). Socks and sports shoes were worn during the stop-jump to minimise potential injury. The kinetic and kinematic were time synchronised and collected using First Principles software (Version 1.00.2, Northern Digital, Waterloo, Canada).

**Data Reduction**

Analysis of the kinematic and kinetic data was performed using Visual 3D software (Version 3, C-Motion, Germantown, Maryland, USA). The raw ground reaction force data were initially filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter ($f_c = 50$ Hz) before calculating the ground reaction
force variables. The raw kinematic coordinates, ground reaction forces, free moments and center of pressure data were then filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter ($f_c = 18$ Hz) before calculating individual joint kinematics, knee joint moments and patellar tendon forces (11,26). The patellar tendon forces were calculated by dividing the knee joint moment by the patellar tendon moment arm (27). Patellar tendon moment arms were calculated as a function of knee joint angle using the method of Herzog & Read (28).

**Data Analysis**

The jump height attained by each participant during the stop-jump movement was defined as the difference in the maximum vertical displacement of the greater trochanter marker minus the vertical displacement of the same marker measured while each participant stood motionless. The two landing phases within the stop-jump movement were then identified from the vertical ground reaction force-time curve as (i) the “horizontal” landing phase and (ii) the “vertical” landing phase (Figure 8). The primary outcome variable analysed during these two landing phases was the peak patellar tendon force ($F_{PT}$). Secondary variables analysed during the same two landing phases included the peak knee joint moment, the peak vertical ground reaction force ($F_V$), the peak posterior ground reaction force ($F_{AP}$) and the ankle, knee and hip joint kinematics. Loading rate of the $F_V$ (LR $F_V$, BW.$s^{-1}$) was calculated by dividing the $F_V$ by the time interval between initial foot-ground contact (IC) to the time of the $F_V$. Loading rate of the $F_{PT}$ (LR $F_{PT}$, BW.$s^{-1}$) was calculated by dividing the $F_{PT}$ by the time interval between IC to the time of the $F_{PT}$. The temporal events (IC, and the times of the peak $F_V$ and $F_{AP}$) were defined using the 18 Hz filtered kinetic data, with initial contact defined when the ground reaction force exceeded 30 N.
Figure 8. The five phases of the stop-jump movement identified from the vertical ground reaction force-time curve include: (1) preparation for the horizontal landing; (2) the first horizontal landing phase; (3) preparation for the take-off of the vertical jump; (4) preparation for the vertical landing; and (5) the vertical landing phase. IC = initial foot-ground contact; \( F_V \) = peak vertical ground reaction force; \( F_{PT} \) = peak patellar tendon force.

Statistical Analysis

Means and standard deviations were calculated for each kinetic and kinematic variable during the horizontal and vertical landing phases. After confirming normality and equal variance, the data were analysed using paired \( t \)-tests to determine whether there were any significant differences (\( P < 0.05 \)) in the primary and secondary outcome variables between the two landing phases. Although multiple statistical tests were conducted, increasing the chance of incurring error, no adjustment to the \( \alpha \) level was deemed necessary given the exploratory nature of the study and the low cost associated with incurring a Type I error.
RESULTS

Patellar Tendon Loading and Ground Reaction Forces

During the horizontal landing phase the participants generated a significantly higher mean $F_{PT}$ ($P = 0.03$), a higher patellar tendon loading rate ($P < 0.001$), a higher mean knee joint moment ($P = 0.02$), and a shorter time to reach the $F_{PT}$ ($P = 0.02$) compared to during the vertical landing phase (Figure 9). The participants also took significantly less time to reach the $F_V$ ($P < 0.001$) and $F_{AP}$ ($P < 0.001$), generated a lower mean $F_V$ ($P = 0.002$) but a higher $F_{AP}$ ($P < 0.001$; Figure 9) during the horizontal landing phase relative to the vertical landing phase. Figure 10 illustrates a representative trial for a single participant during the stop-jump task of the patellar tendon and the ground reaction forces, as well as ankle, knee and hip joint angles.

![Figure 9](image_url)

**Figure 9.** Mean (± SD) of the forces generated during the horizontal and vertical landing phases of a stop-jump movement (normalised to body weight) of 16 male participants with healthy patellar tendons. (A) Peak vertical ground reaction force ($F_V$), peak anterior-posterior ground reaction force ($F_{AP}$), peak patellar tendon forces ($F_{PT}$) and peak knee joint moment. (B) The loading rate of the $F_V$ (LR $F_V$) and the loading rate of the $F_{PT}$ (LR $F_{PT}$). (C) The time from initial foot-ground contact (IC) to the time of the $F_V$ (IC to $F_V$), the time from IC to the time of the $F_{AP}$ (IC to $F_{AP}$) and the time from IC to the time of the $F_{PT}$ (IC to $F_{PT}$). *Indicates a significant difference ($P < 0.05$) between the landing phases.
Figure 10. Representative data for the ankle, knee and hip joint angles (°), and the patellar tendon and ground reaction forces (BW) for a single participant with healthy patellar tendons during the horizontal and vertical landing phases of a stop-jump task. Peak vertical ground reaction force ($F_V$); peak anterior-posterior ground reaction force ($F_{AP}$); peak patellar tendon force ($F_{PT}$). Note the section between the vertical dotted lines indicates the landing phase within the stop-jump task.

Joint Kinematic Data

During the vertical landing phase, the participants landed in significantly greater plantar flexion at IC ($P < 0.001$) and then began to dorsiflex their ankle joint to achieve a greater magnitude of dorsiflexion at the times of the $F_V$ ($P < 0.001$) and $F_{PT}$ ($P < 0.001$) relative to during the horizontal landing phase (Figure 11). In contrast, during the horizontal landing phase the participants maintained a relatively unaltered dorsiflexion position from IC to the time of $F_{PT}$, resulting in significantly less dorsiflexion velocity at the time of the $F_V$ ($P = 0.01$; Figure 12). These differences in ankle posture at landing were accompanied by significant differences in tibial alignment.
Figure 11. Mean (± SD) joint angles (°) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force (F_V) and at the time of the peak patellar tendon force (F_PT) during the two landing phases of the stop-jump task of 16 male participants with healthy patellar tendons. *Indicates a significant difference (P < 0.05) between the landing phases.

(Figure 13), whereby during the horizontal landing phase the participants inclined their tibial segment in the sagittal plane with their knee joint posterior to the ankle joint at IC (17.6° ± 3.5°) and at the time of the F_V (7.8° ± 5.6°), adopting a relatively vertical tibial alignment (-1.5° ± 5.3°) by the time of the F_PT. In contrast, during the vertical landing phase the participants inclined their tibial segment in the sagittal plane with their knee joint anterior to the ankle joint at the time of IC (-7.3° ± 3.6°; P < 0.001), with the knee joint continuing to move further anterior relative to the ankle joint by the time of the F_V.
Figure 12. Mean (± SD) joint velocities (°.s⁻¹) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force (Fᵥ) and at the time of the peak patellar tendon force (Fₚₜ) during the two landing phases of the stop-jump task of 16 male participants with healthy patellar tendons. *Indicates a significant difference (P < 0.05) between the landing phases.

(-24.7° ± 5.4°; P < 0.001) and at the time of the Fₚₜ (-29.6° ± 4.8°; P < 0.001).

Although both groups inverted their ankle during the landing phase from IC to the time of Fₚₜ, during the horizontal landing phase there was relatively less ankle inversion at the times of the Fᵥ (P < 0.001) and Fₚₜ (P = 0.02) compared to the vertical landing phase. The participants also displayed significantly more forefoot abduction at IC (P < 0.001) during the horizontal landing phase, though the forefoot adduction velocity was
Figure 13. Lower limb alignment during the horizontal and vertical landing phases of a stop-jump movement at initial foot-ground contact (IC) and at the time of the peak patellar tendon force ($F_{PT}$). Note the more posterior direction of the vertical ground reaction force vector and the altered tibial alignment during the horizontal landing phase compared to the vertical landing phase.

Significantly greater at the time of the $F_{PT}$ ($P = 0.05$) compared to vertical landing phase.

Participants displayed significantly more knee flexion at IC during the horizontal compared to the vertical landing phase, although they displayed similar knee flexion angles at the times of the peak $F_V$ and $F_{PT}$ during the two landing phases (Figure 11). Knee flexion velocity was, however, significantly greater at the time of the peak $F_V$ ($P = 0.04$) during the horizontal landing phase compared to the vertical landing phase, despite the smaller range of motion that the knee moved through from the time of IC to the time of $F_{PT}$. Although there was no between-phase difference in the adduction/abduction angle at the knee joint, participants displayed significantly greater
knee abduction velocity at both IC ($P = 0.02$) and the time of the F$_{PT}$ ($P = 0.02$) during the horizontal landing phase compared to the vertical landing phase.

Hip kinematics during the horizontal landing phase demonstrated that the participants landed with greater hip flexion at IC ($P < 0.001$) at the time of the F$_{V}$ ($P < 0.001$) and at the time of the F$_{PT}$ ($P < 0.001$), despite flexing their hips at a slower velocity at the times of the F$_{V}$ ($P = 0.02$) and F$_{PT}$ ($P < 0.001$) compared to during the vertical landing phase. During the horizontal landing, the participants also displayed significantly less hip abduction ($P = 0.03$) and slower hip abduction velocity at the time of the F$_{PT}$ ($P = 0.03$) compared to during the vertical landing phase. Although the angle of hip rotation was similar for both landing tasks at IC, during the horizontal landing phase the participants internally rotated their hips significantly more at the times of the F$_{V}$ ($P = 0.01$) and F$_{PT}$ ($P = 0.05$) and with faster hip internal velocity at the time of the F$_{V}$ ($P = 0.03$) compared to during the vertical landing phase (Figure 11 and Figure 12).

DISCUSSION

This study quantified the patellar tendon loads generated by asymptomatic athletes with normal patellar tendons during the horizontal and vertical landing phases of a dynamic landing movement. In agreement with our hypothesis, the two landing phases differed significantly in terms of the forces generated at landing, with the participants generating significantly higher F$_{PT}$ and F$_{AP}$, yet significantly lower F$_{V}$ during the horizontal landing phase compared to the vertical landing phase. Interestingly, if the peak F$_{V}$ was used to represent peak patellar tendon loading in the present study, the horizontal landing phase would errantly be viewed as generating less force on the patellar tendon than the vertical landing phase. These findings reinforce the notion that the F$_{V}$ should not be used to reflect the F$_{PT}$. The significantly greater peak F$_{PT}$ and F$_{PT}$ loading rate and the less time taken from IC to reach the F$_{V}$ or F$_{PT}$
during the horizontal landing phase, suggests that these higher patellar tendon loads may create a greater potential risk of overloading the patellar tendon compared to during vertical landings.

Ankle dorsiflexion was significantly less during the horizontal landing phase compared to vertical landing phase. Malliaras et al. (29) cautioned that reduced ankle dorsiflexion range during landing may increase the risk of developing patellar tendinopathy by limiting the range of motion over which the ankle joint plantar flexor muscles can act, in turn, causing the knee and hip extensor groups to have to contribute more to this force dissipation (13). The limited dorsiflexion range of movement combined with the lower ankle dorsiflexion velocity displayed by the participants during the horizontal landing phase may have contributed to the higher patellar tendon load compared to that sustained during the vertical landing phase.

In comparison to this study, similar (19,21,23,24,30) and varied (24) values have previously been reported for knee and hip joint angles during the horizontal landing phase of the stop-jump movement. Several studies have suggested that increased knee flexion during landing was a strong predictor of patellar tendinopathy, whereby athletes with patellar tendinopathy landed with more knee flexion at initial contact (2) and at the time of the \( F_V \) (7,8). It was hypothesised that landing with more knee flexion might not only contribute to the higher patellar tendon force observed in the horizontal landing phase, but as the patellar tendon is oriented anteriorly at knee flexion angles >60° (31), it may also lead to greater compression of the posterior aspect of the patellar tendon against the patella (32). Greater compression of the patellar tendon has been suggested to be a cause of proximal patellar tendinopathy (33,34). We speculate that landing with greater hip flexion during the horizontal landing phase may potentially add to this compression as the total body centre of mass would be located more posterior to the
base of support, creating a greater horizontal shear force at the knee joint (Figure 13). As a result of these compressive forces, patellar tendon adaptation may occur in the form of increasing the amount of fibrocartilage, which is known to resist compressive and shear forces (35). It is thought this tendon adaptation may be at the expense of tissue that resists tensile loading, which may, in turn, decrease load tolerance and ultimately overload of the patellar tendon (34).

Despite the significantly lower $F_V$ in the horizontal landing phase, the $F_{PT}$ was significantly greater relative to during the vertical landing phase. The $F_{PT}$ is derived by dividing the knee joint moment by the patellar tendon moment arm. Knee joint moments are calculated via a complex equation incorporating both the kinetics and kinematics characterising the lower limb during the landing action (36). In the present study, variations in the patellar tendon moment arm could not explain between-phase differences in the $F_{PT}$ as the participants displayed similar amounts of knee joint flexion at $F_{PT}$ during the two landing phases (28). Therefore, the significantly higher knee joint moment was attributed to the significantly higher $F_{PT}$ found in the horizontal landing phase (Figure 9). We speculate that the higher knee joint moment was primarily due to the direction of the vector of the resultant ground reaction force, which created a larger knee joint moment arm by increasing the perpendicular distance between the knee joint centre of rotation and the centre of pressure of the resultant ground reaction force vector (Figure 13). In addition, the higher knee joint moment may also have been influenced by the significantly different tibial alignment (Figure 13), significantly faster tibial segment velocity and the significantly higher $F_{AP}$ relative to the vertical landing task, which is consistent with previous research (9).

Utilization of the stretch-shortening cycle during a movement task increases the $F_{PT}$ as a result of the countermovement, which passively and then actively lengthens the
muscles to take advantage of the muscle’s length-tension properties to enhance velocity and power in the subsequent takeoff phase (9). We speculate that the significantly higher $F_{PT}$ generated during the horizontal landing phase may be in part due to the fact that this phase immediately preceded preparation for the subsequent vertical jump phase of the stop-jump movement. In contrast the vertical landing phase was the terminal phase of the stop-jump movement and therefore was isolated from any countermovement. Anticipation of the subsequent vertical jump during the horizontal landing phase may have also dictated the need for the participants to use greater knee flexion at IC in preparation for the takeoff phase than would typically be used in an isolated horizontal landing movement, in which the knee joint is relatively extended at IC (37). These findings provide further evidence that laboratory-based investigations should replicate game-like movements (38).

A “stiffer” landing strategy has also been previously associated with an increased risk of developing patellar tendinopathy (2,6-8). A “stiffer” strategy has been previously characterized by a faster rate of landing (7,8), which participants displayed during the horizontal landing phase in the present study by faster knee joint flexion velocity. However, a stiffer landing strategy has also been characterized by landing with a relatively extended knee joint, which is then forced into knee flexion (2,6), a strategy that was displayed during the vertical landing phase in the present study. It should be noted that stiffness has been described using a variety of different definitions and methods of calculation and can be independent of time, length or velocity (39). As stiffness reflects a change in force related to a change in muscle length, stiffness can actually be independent of where in the range of knee flexion the muscle length change may occur. The results of this study therefore highlight the need to clearly define what is meant by a “stiffer” landing strategy.
We acknowledge that there are limitations in the current experimental design. The two-dimensional model used to estimate patellar tendon force has limitations in that it could potentially underestimate the patellar tendon force because it uses the net knee joint moment to estimate patellar tendon force. This calculation does not account for the flexor moment produced by the hamstring or gastrocnemius muscles, which must be compensated for by a higher knee extensor moment (40). It has been suggested that the patellar tendon should be modeled three-dimensionally due to its orientation in the sagittal and coronal planes. However, only two-dimensional linear regression equations exist for the patellar tendon (28,41). These limitations should be addressed by developing a three-dimensional patellar tendon model that can be implemented in future studies to confirm our findings.

**CONCLUSIONS**

This study provides a framework to investigate the biomechanical variables of landing associated with patellar tendinopathy. Significantly higher patellar tendon forces but lower vertical ground reaction forces were generated during the horizontal landing phase of the stop-jump task compared to the vertical landing phase, questioning the validity of using vertical ground reaction forces to reflect patellar tendon forces during the stop-jump movement. The higher patellar tendon loads sustained during the horizontal landing phase are thought to have been caused by limited ankle dorsiflexion, greater knee and hip flexion and utilization of the stretch-shortening cycle during the horizontal landing phase compared to the vertical landing phase. We speculate that these between-phase differences may have lead to the higher patellar tendon loads and greater compression of the posterior aspect of the proximal patellar tendon during the horizontal landing phase. Together, these effects indicate that the horizontal landing phase of a stop-jump movement places the highest load on the patellar tendon, which
Part II: Chapter 4

may potentially lead to patellar tendinopathy. Future research investigating lower limb landing mechanics in athletes with patellar tendinopathy should preferably utilise a horizontal landing task in order to ensure the most appropriate framework to investigate lower limb landing strategies and risk factors associated with patellar tendinopathy in repetitive landing sports.

REFERENCES


Part II: Chapter 4

**muscle activation patterns during landing in beach volleyball?** Paper presented at the 18th International Society of Biomechanics Congress, Zurich (Switzerland).


Chapter 5

Alterations to Landing Technique and Patellar Tendon Loading in Response to Fatigue

This chapter is an amended version of the manuscript: Edwards S, Steele JR, Purdam CR, Cook JL, McGhee DE. Alterations to landing technique and patellar tendon loading in response to fatigue. *Medicine & Science in Sports & Exercise*. Submitted for publication February, 2010.

ABSTRACT

Purpose

Fatigue may contribute to knee joint injuries, such as patellar tendinopathy, via increasing joint loading and altering lower limb landing technique. This study aimed to investigate the effect of muscle fatigue on the landing technique and patellar tendon loads generated during the horizontal and vertical landing phases of a stop-jump movement. It was hypothesised that muscle fatigue would increase patellar tendon loading and alter the landing technique displayed during the horizontal landing phase but not the vertical landing phase of the stop-jump task.

Methods

Sixteen men with healthy patellar tendons, recruited from team sports involving repetitive landing, performed repeated trials of a stop-jump task. During each trial, the participants’ ground reaction forces (GRF) and electromyographic activity of seven lower limb muscles were recorded, three-dimensional kinematics measured, and peak patellar tendon force (F<sub>PT</sub>) calculated by dividing the net knee joint moment by the patellar tendon moment arm.
Results

When fatigued, participants generated a significantly lower $F_{\text{PT}}$ ($p = 0.014$) and $F_{\text{PT}}$ loading rate ($p = 0.018$) despite a higher vertical GRF ($F_V$; $p = 0.003$) and $F_V$ loading rate ($p = 0.002$) during the horizontal landing phase. During the vertical landing phase, participants displayed similar lower limb landing strategies irrespective of fatigue condition.

Conclusions

During the horizontal landing task when fatigued, participants decreased their patellar tendon load by altering their lower limb landing strategy, which may have a protective effect and potentially decrease the risk of developing patellar tendon abnormalities and, in turn, patellar tendinopathy. Further research is recommended to ascertain whether these alterations to landing technique can decrease the risk of developing patellar tendinopathy.

INTRODUCTION

Fatigue is thought to be a major risk factor in the development of knee joint injuries (1-4), particularly overuse injuries such as patellar tendinopathy, as a higher incidence of injuries occur towards the end of both halves (2) or in the later part of competitive team games (1,2). Altered lower limb landing strategies have been observed in healthy athletes as a consequence of being fatigued (3-5), as well as athletes suffering patellar tendinopathy (6-10). It is remains unknown, however, whether fatigue-induced alterations to an athlete’s lower limb landing technique contribute to an increased risk of developing patellar tendinopathy in sports, such as soccer, basketball or volleyball, which involve both repetitive landings and incur a high prevalence of patellar tendinopathy (11).
Although there has been extensive research investigating the effects of fatigue on the technique used by athletes to land, the results of these studies are disparate. Between-study differences in the results are mainly due to differences in experimental design, including differences in the experimental movement task (12,13) and/or the protocol used to induce subject fatigue (13,14). Interestingly, research investigating fatigue effects (3,5,15,16) and/or possible mechanisms of patellar tendinopathy (5,8) have predominantly been restricted to examining vertical landing tasks as the experimental movement. Experimental movement tasks, however, should replicate game-like situations (5,17-19) and vertical landing tasks, in which the landing phase is isolated from the whole jump-landing task, have limited application as they are rarely performed in game-like situations. A more common movement task in game-like situations within many teams sports is a horizontal landing task (4,20,21). Furthermore, compared to a vertical landing task, the horizontal landing phase of a stop-jump movement places the highest load on the patellar tendon, which may potentially lead to patellar tendinopathy (22). Therefore, research investigating factors affecting the lower limb landing technique of athletes, with implications for developing patellar tendinopathy, should preferably utilise a horizontal landing task in order to ensure the most appropriate experimental framework to better identify possible risk factors associated with development of patellar tendinopathy in repetitive landing sports (22).

Disparate results relating to fatigue effects and landing technique can also be attributed to differences in the protocols used to induce fatigue. The validity of previous fatigue protocols has been limited (3,23) by factors such as the range of lower limb motion typically displayed during dynamic landing tasks not being replicated in the experimental design, and the rest intervals tested being inconsistent with the stop-start nature of game-like conditions (23). Furthermore, despite previous research
showing high response variability and large inter-individual variations as an effect of fatigue (24,25), the reliability of previous fatigue protocols has not been established.

This study aimed to investigate the effect of fatigue on the landing technique and patellar tendon loads generated by asymptomatic athletes with normal patellar tendons during the horizontal and vertical landing phases of the stop-jump movement. In order to overcome previous research limitations in experimental design described above, the experimental movement was a landing task that was common to sports with a high incidence of patellar tendinopathy, the stop-jump movement (15,20), and involved both a horizontal and vertical landing phase. Furthermore, a valid and reliable fatigue protocol, which has previously been developed to investigate lower limb fatigue during a dynamic landing task (23), was used to induce lower limb fatigue. It was hypothesised that fatigue would increase participants’ patellar tendon loading and alter their landing technique during the horizontal landing phase but not the vertical landing phase of the stop-jump task.

**METHODS**

**Participants**

Sixteen skilled male basketball, soccer and volleyball athletes (mean age = 22.4 ± 2.9 years; height = 182.1 ± 8.7 cm; mass = 75.7 ± 10.1 kg) volunteered as study participants. All the participants were right leg dominant, based on their preferred kicking leg (26), and reported no history of traumatic lower limb injuries. Each participant’s patellar tendon morphology was documented as normal by an experienced musculoskeletal radiologist using a 13 MHz linear array ultrasound transducer (Siemens Antares, Siemens AG, Germany). Written informed consent was obtained from each participant prior to data collection and all the study’s methods were approved by the University of Wollongong Human Research Ethics Committee (HE06/205).
**Experimental Protocol**

No less than one week prior to data collection, participants performed a familiarisation session of the study protocol, which included a 5-10 minute warm-up, a familiarisation of the stop-jump task before the fatigue protocol, and completed a full trial of the fatigue protocol (23). The participants then returned to the Biomechanics Research Laboratory on a second occasion for data to be collected during the full experimental protocol, which involved the warm-up followed by standardised trials of the stop-jump task both before and after the fatigue protocol (Figure 14).

**Experimental Task**

The stop-jump task consisted of a horizontal landing phase, immediately followed by a vertical landing phase. The horizontal landing phase required the participants to accelerate forwards for four steps towards two force platforms, to stop and perform the simultaneous two-foot landing with their right and left feet contacting a separate force platform. The vertical landing phase immediately followed and required the participants to jump vertically upwards to strike a ball suspended from the ceiling with both hands and to then perform the simultaneous two-foot landing a second time with each foot again contacting a separate force platform. During the stop-jump task familiarisation, the effort among the participants at which they performed the task was standardised by using a set starting position away from the force platform. The participants’ average approach speed was measured immediately before the preparation phase of the first landing, using infrared timing lights (OnSpot, University of Wollongong). Jump height effort was standardised among the participants by positioning the ball at the maximum height each participant could touch the ball with both hands after performing the stop-jump movement during task familiarisation.
Figure 14. Flow chart illustrating the experimental protocol.
Before performing the stop-jump task, each participant’s ankle joint range of motion (27), height, body mass and lower limb dimensions were evaluated as descriptive characteristics of the participant cohort and for later input into inverse dynamic modelling.

**Fatigue Protocol**

The protocol utilised to induce lower limb fatigue, which has previously been found to be valid and reliable, is described in detail elsewhere (23). In brief, it required the participants to repeatedly perform sets of 30 submaximal rebound exercises on a sledge apparatus immediately followed by 30 seconds rest. Fatigue was deemed when the participant could no longer achieve 70% of their maximal rebound height for three out of five rebound exercises or when participants self terminated the sets as they felt that they could no longer continue. An increase in post-fatigue blood lactate levels to at least 6 mmol/L, analysed using an Accusport blood lactate analyser (Boehringer Mannheim, Germany) was also measured at the end of the experimental protocol to confirm fatigue.

**Experimental Procedures**

During each stop-jump trial the ground reaction forces generated during each landing were recorded (1000 Hz) using two multichannel force platforms (Type 9281B; Type 9253B; Kistler, Winterthur, Switzerland) embedded in the floor, with each platform connected to a multichannel charge amplifier (Type 9865A; Type, 9865B; Kistler, Winterthur, Switzerland). The participant’s three-dimensional lower limb motion was recorded (100 Hz) using an OPTOTRAK® 3020 motion analysis system (Northern Digital, Waterloo, Canada). Infrared light-emitting diodes were placed on each participant’s dominant lower limb and pelvis, on the shoe at the first and fifth metatarsal head and mid-anterior foot, lateral malleolus, medial malleolus, lateral leg,
anterior distal leg, anterior proximal leg, lateral femoral epicondyle, medial femoral epicondyle, lateral femur, anterior distal femur, anterior proximal femur, greater trochanter, anterior superior iliac spine and iliac crest. To avoid losing view of the infrared light-emitting diodes, the participants wore minimal clothing (a t-shirt and shorts). Socks and sports shoes were worn during the stop-jump task.

Electromyographic activity was recorded bilaterally for vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), tibialis anterior (TA), and medial gastrocnemius (MG) using two TeleMyo systems (Noraxon, Arizona, USA). Following standard preparation (28), bipolar silver-silver-chloride surface electrodes (Ambu® Blue Sensor M, electrode size = 40.8 x 32 mm, detection area = 13.2 mm²) were placed longitudinally on each muscle belly (inter-electrode distance of 20 mm). A common reference electrode was located on the tibial tuberosity of each lower limb. The electromyographic signals for each lower limb were sampled (1000 Hz, bandwidth 16-500 Hz) and relayed from two TeleMyo 900 battery powered transmitters (Noraxon, Arizona, USA), firmly fixed around the participant’s waist, to two TeleMyo 900 receivers. The kinetic, kinematic and electromyographic data were time synchronised and collected using First Principles software (Version 1.00.2, Northern Digital, Waterloo, Canada).

Data Reduction

Analysis of the kinematic and kinetic data was performed using Visual 3D software (Version 3, C-Motion, Maryland, USA). The raw ground reaction force data were initially filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter ($f_c = 50$ Hz) before calculating the ground reaction force variables. The raw kinematic coordinates, ground reaction forces, free moments and center of pressure data were then filtered using a fourth-order zero-phase-shift Butterworth digital low pass
Part II: Chapter 5

filter \( f_c = 18 \text{ Hz} \) before calculating individual joint kinematics, internal knee joint moments and patellar tendon forces \((3,29)\). The patellar tendon forces were calculated by dividing the net knee joint moment by the patellar tendon moment arm \((30)\). Patellar tendon moment arms were calculated as a function of knee joint angle using the method of Herzog & Read \((31)\).

The raw electromyographic signals were filtered using a fourth-order zero-phase shift Butterworth \((\text{high-pass } f_c = 15 \text{ Hz})\) to eliminate any movement artefact. To quantify temporal characteristics of the muscle bursts, the filtered electromyographic data were full-wave rectified, filtered with a 20 Hz low pass filter and then full-wave rectified to create linear envelopes that were then screened using a threshold detector \((8\% \text{ of the maximum amplitude}) \,(32)\) using customized software \((\text{LabVIEW 8, National Instruments})\). Each individual muscle’s filtered signal was visually inspected to confirm the validity of the calculated results of the temporal characteristics of the muscle bursts to minimise the probability of error.

**Data Analysis**

The two landing phases within the stop-jump movement were firstly identified from the vertical ground reaction force trace: (i) the “horizontal” landing phase and (ii) the “vertical” landing phase \((22)\). The primary outcome variable analysed during these two landing phases was the peak patellar tendon force \((F_{PT})\). Secondary variables analysed during the same two landing phases included the peak vertical ground reaction force \((F_V)\) and peak anterior-posterior ground reaction force \((F_{AP})\); ankle, knee and hip joint kinematics; the peak knee joint moment; and the time of the onset and peak muscle activity of each of the seven lower limb muscles relative to the time of the \(F_{PT}\) in each landing phase. Loading rate of the \(F_V\) \((LR F_V, \text{BW.s}^{-1})\) was calculated by dividing the \(F_V\) by the time interval between initial foot-ground contact \((IC)\) to the time of the \(F_V\).
Loading rate of the F_P (LR F_P, BW.s^{-1}) was calculated by dividing the F_P by the time interval between IC to the time of the F_P. The temporal events (IC, and at the time of the peak F_V and F_AP) were defined using the 18 Hz filtered kinetic data, with initial contact defined when the ground reaction force exceeded 30 N. The jump height (cm) attained by each participant during the stop-jump movement was also calculated as the difference in the maximum vertical displacement of the greater trochanter marker minus the vertical displacement of the same marker measured while each participant stood motionless.

Statistical Analysis

Means and standard deviations were calculated for each kinetic, kinematic and muscle activity variable during the horizontal and vertical landing phases in a non-fatigued (NF) and fatigued (F) condition. After confirming normality and equal variance, the data were analysed using paired t-tests to determine whether there were any significant differences (p < 0.05) in the primary and secondary outcome variables between the non-fatigued and fatigued conditions. Although multiple statistical tests were conducted, increasing the chance of incurring error, no adjustment to the alpha level was deemed necessary given the exploratory nature of the study and the low cost associated with incurring a Type I error (22).

RESULTS

Fatigue Variables

During the fatigue protocol, participants performed on average 14.5 ± 9.6 fatigue sets and displayed a significant increase in post-fatigue blood lactate level above the 6 mmol/L fatigue criterion (NF = 3.4 ± 0.7 mmol/L; F = 8.0 ± 1.9 mmol/L; p < 0.001).

Despite attempts to standardize both the approach speed and vertical jump height achieved during the stop-jump task, fatigue lead to a significant decrease in the
participants’ average approach speed (NF = 4.5 ± 0.4 m/s; F = 4.1 ± 0.4 m/s; \( p < 0.001 \)) and the average vertical jump height attained (NF = 49 ± 5 cm; F = 45 ± 6 cm; \( p = 0.02 \)) during the stop-jump task.

**Horizontal Landing**

![Horizontal Landing Diagram](image)

**Vertical Landing**

![Vertical Landing Diagram](image)

**Figure 15.** Mean (± SD) of the forces generated during the horizontal and vertical landing phases of a stop-jump task (normalised to body weight) of athletes of 16 male participants with healthy patellar tendons. (A) Peak vertical ground reaction force (F\(_V\)), peak anterior-posterior ground reaction force (F\(_{AP}\)), peak patellar tendon forces (F\(_{PT}\)) and peak knee joint extension moment. (B) The loading rate of the F\(_V\) (LR F\(_V\)) and the loading rate of the F\(_{PT}\) (LR F\(_{PT}\)). (C) The time from initial foot-ground contact (IC) to the time of the F\(_V\) (IC to F\(_V\)), the time from IC to the time of the F\(_{AP}\) (IC to F\(_{AP}\)) and the time from IC to the time of the F\(_{PT}\) (IC to F\(_{PT}\)). *Indicates a significant between-fatigue condition difference (\( p < 0.05 \)).
**Patellar Tendon Loading**

During the horizontal landing phase, participants generated a significantly lower mean $F_{PT}$ ($p = 0.014$), LR $F_{PT}$ ($p = 0.018$; Figure 15) and peak knee joint moment ($p = 0.023$) when fatigued compared to when non-fatigued. In contrast, during the vertical landing phase, there was no significant between-fatigue condition difference in patellar tendon loading or knee joint moment.

**Ground Reaction Forces**

When fatigued during the horizontal landing phase, the participants displayed a significantly higher $F_{V}$ ($p = 0.003$) and LR $F_{V}$ ($p = 0.002$) and a shorter duration from IC to the time of the $F_{V}$ over which to sustain these loads ($p = 0.014$). During the vertical landing phase, the only significant between-fatigue condition difference was a significantly greater $F_{AP}$ during the fatigued condition compared to the non-fatigued condition ($p < 0.001$; Figure 15).

**Joint Kinematic Data**

During the horizontal landing phase, the participants maintained similar ankle joint positions from IC to the time of the $F_{PT}$ during both the fatigued and non-fatigued conditions. In fact, the only difference in ankle kinematics the participants displayed when fatigued was a significantly slower forefoot abduction velocity at the time of the $F_{V}$ ($p = 0.018$) compared to when non-fatigued. In contrast, during the horizontal landing phase participants landed with significantly less knee flexion at the time of all three critical events (IC $p = 0.022$; $F_{V}$ $p < 0.001$; $F_{PT}$ $p = 0.031$) when fatigued compared to when non-fatigued. However, knee flexion velocity and the range of knee joint motion from the time of IC to the time of $F_{PT}$ (NF = 50 ± 12°; F = 50 ± 10°; $p = 0.805$) were similar during both the fatigued and non-fatigued conditions. When fatigued, the participants displayed significantly less hip flexion throughout the
Figure 16. Means (± SD) of joint angles (°) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force (Fv) and at the time of the peak patellar tendon force (FPT) during the two landing phases of the stop-jump task during the non-fatigued (NF) and fatigued (F) conditions of 16 male participants with healthy patellar tendons. *Indicates a significant between-fatigue condition difference (p < 0.05).

Horizontal landing phase (IC p = 0.012; Fv p < 0.001; FPT p = 0.047). Hip abduction was also significantly less when fatigued compared to non-fatigued; although this was only at the time of the FPT (p = 0.025). Although participants flexed their hips to a similar extent when both fatigued and non-fatigued during the horizontal landing phase, hip flexion velocity at IC (p = 0.046) was significantly slower when the participants landed fatigued, even though hip flexion velocity was significantly faster at the time of...
**Figure 17.** Means (± SD) of joint velocities (°·s⁻¹) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force (Fᵥ) and at the time of the peak patellar tendon force (Fₚₜ) during the two landing phases of the stop-jump task of 16 male participants with healthy patellar tendons. *Indicates a significant between-fatigue condition difference (p < 0.05).

the Fₚₜ (p = 0.034) when the participants were fatigued compared to when non-fatigued (Figure 16 and Figure 17).

During the vertical landing phase, the participants displayed a significantly more plantar flexed position of the ankle (p = 0.005) and a higher plantar flexion velocity (p = 0.007) at IC when fatigued compared to when non-fatigued. Furthermore, the participants underwent a significantly smaller ankle plantar flexion-dorsiflexion range of motion from the time of IC to the time of the Fₚₜ (NF = 55 ± 7°; F = 49 ± 8°; =
Part II: Chapter 5

0.005) when fatigued. A significantly slower knee flexion velocity at IC ($p \leq 0.001$), a faster knee abduction velocity at both the IC ($p = 0.024$) and the time of the $F_V$ ($p = 0.003$), and a smaller range of motion from the time of IC to the time of the $F_{PT}$ (NF = 55 ± 7°; F = 49 ± 8°; $p = 0.006$) were also all evident during the fatigued condition compared to the non-fatigued condition when the participants landed vertically. Furthermore, participants displayed significantly less hip abduction at IC ($p = 0.046$) and at the time of the $F_{PT}$ ($p = 0.021$) during the vertical landing phase when fatigued compared to when non-fatigued (Figure 16 and Figure 17).

Muscle Activation Patterns

During the horizontal landing phase the participants used a relatively similar muscle recruitment strategy to stabilize their lower limbs during both the non-fatigued and fatigued conditions. Nevertheless, when landing horizontally participants displayed a significantly later peak muscle burst activity for BF ($p = 0.010$) and VL ($p = 0.049$) relative to the time of the $F_{PT}$ during the fatigued condition compared to the non-fatigued condition (Figure 18B). In contrast, during the vertical landing phase, the participants used a relatively different muscle activation patterns strategy to stabilize their lower limbs when fatigued compared to when non-fatigued. That is, when fatigued, participants displayed a significantly later onset of ST ($p = 0.004$), BF ($p = 0.004$) and TA ($p = 0.039$) (Figure 18A), and a significantly later peak muscle burst activity for MG ($p = 0.013$), BF ($p = 0.008$) and TA ($p = 0.019$) relative to the time of the $F_{PT}$ activity compared to when non-fatigued (Figure 18B).
Figure 18. Means (± SD) for the times of the (A) onset of muscle activity relative to the time of the FPT, represented as Time 0, and (B) Peak muscle activity relative to the time of the FPT, represented as Time 0, during the two landing phases of the stop-jump task. Negative values indicate muscle activation variable occurred before the time of the FPT; VL = vastus lateralis; RF = rectus femoris; VM = vastus medialis; ST = semitendinosus; BF = biceps femoris; MG = medial gastrocnemius; TA = tibialis anterior. *Indicates a significant between-fatigue condition difference ($p < 0.05$) during the horizontal landing phase of a stop-jump task. # Indicates a significant between-fatigue condition difference ($p < 0.05$) during the vertical landing phase of a stop-jump task.
DISCUSSION

The primary extrinsic risk factor associated with patellar tendinopathy is repetitive landing (33-37). We originally hypothesised that fatigue would exacerbate this risk by increasing the magnitude of these repetitive loads sustained by the patellar tendon during the horizontal landing phase. In contrast to our hypothesis, however, both the $F_{PT}$ and LR $F_{PT}$ significantly decreased during the fatigued condition, despite significant increases in both the $F_{V}$ and LR $F_{V}$ generated during the same condition. Reasons for this unexpected finding are discussed below. This result, however, confirms previous research (22) that $F_{V}$ is not a reliable indicator of $F_{PT}$. That is, if $F_{V}$ had been used as a surrogate of $F_{PT}$ in the present study, it would have been errantly concluded that fatigue increased patellar tendon loading during the horizontal landing phase, when fatigue in fact reduced patellar tendon loading. As hypothesised, these differences in patellar tendon loading as a consequence of fatigue were not found during the vertical landing phase.

Most of the significant between-fatigue condition differences were evident during the horizontal landing phase rather than the vertical landing phase. This finding highlights the limitation of previous studies that have only used vertical landings as the experimental movement to examine lower limb landing strategies in relation to patellar tendinopathy (6,8,9,38). The lower magnitude of patellar tendon force during the vertical landing phase (22) may explain why most of the fatigue effects were observed during the horizontal landing phase. It also assists to explain some of the discrepancies in results previously found in research investigating how fatigue affects landing technique.

Consistent with previous research of a stop-jump task, participants in the present study displayed significantly less knee flexion when they were fatigued compared to
when they were non-fatigued during the horizontal landing (4) and during a SSC exercise (39). This reduction in knee flexion during the horizontal landing phase of a stop-jump task when fatigued may be a compensatory effect of fatigue, in which the participants are unable to generate an adequate net knee extension moment upon landing. As the direction of the patellar tendon force is a function of knee joint angle (31), landing with less knee flexion lead to less compressive load on the patellar tendon.

Irrespective of this reduced knee flexion, using the stretch-shortening cycle during a movement task increases the \( F_{PT} \) because of the countermovement, which passively and then actively lengthens the muscles to take advantage of the muscle’s length-tension properties to enhance velocity and power in the subsequent takeoff phase (40). Our previous research has highlighted that in a stop-jump task, the need to prepare to perform a vertical jump immediately after the horizontal landing phase may cause the participants to use greater knee flexion than would typically be used in an isolated horizontal landing movement, in which the knee joint is relatively extended at IC (22). Furthermore, fatigue of the SSC causes participants to land with less knee flexion at IC, decreases the knee extensor positive peak power and decreases the performance of a SSC exercise (39). We speculate that in the present study, landing with less knee flexion during the horizontal landing phase when fatigued reduced the participant’s efficiency in utilising the stretch-shortening cycle muscle action during the subsequent takeoff phase, reflected in the significantly lower jump height and net knee joint moment, but would have protected the knee by significantly reducing the magnitude of the patellar tendon load. Despite this reduction in vertical jump height, the participants were able meet the task requirement of striking the ball, by emphasizing upper body extension rather than raising their total body centre of mass (5).
The $F_{PT}$ is derived by dividing the knee joint moment by the patellar tendon moment arm and thus can be influenced by changes in knee flexion utilised in an activity. In this present study, variations in the patellar tendon moment arm could partially explain the between-fatigue condition differences in the $F_{PT}$, as the participants when fatigued utilised a larger patellar tendon moment arm via landing with significantly less knee joint flexion, which decreased the patellar tendon force compared to when non-fatigued. The significantly lower knee joint moment when fatigued was the primary contributor to the significantly lower $F_{PT}$ found during the horizontal landing phase compared to when non-fatigued. This significant decrease in knee joint moment could not be attributed to the significantly higher $F_V$ and LR $F_V$ when fatigued compared to when non-fatigued, as these both increased and would consequently increase the knee joint moment. We speculate that the significantly lower knee joint moment was attributed to the change in the orientation and position of the body segments, which in turn, altered the direction of the vector of the resultant ground reaction force, characterised by landing with less knee flexion and hip flexion during the horizontal landing phase. By using this landing strategy when fatigued, the participants were less efficient in utilising the stretch-shortening cycle and unable to generate an adequate net knee extension moment upon landing. Our previous research has shown that landing with less knee flexion and hip flexion contributes to a significantly lower knee joint moment (22). As the patellar tendon forces were calculated using the net knee joint moment, the significantly later peak muscle burst activity of BF may have resulted in a higher knee flexion moment which, in turn, may have lead to a lower net knee joint extension moment. In addition, fatigue also led to the participants performing the stop-jump task with a significantly slower approach speed, which may have also contributed to the lower knee joint moment.
Consistent with previous landing studies, the use of a preparatory muscle activation strategy was evident during both landing phases (5,32) and differences existed in the muscle recruitment order displayed during the two landing phases (22). Despite displaying significant kinetic and kinematic differences during the horizontal landing phase when fatigued, the participants maintained a similar lower limb muscle recruitment order, with fatigue resulting only in significantly later peak BF and VL activity relative to the time of the peak F_{PT}. This later peak BF and VL activity when fatigued could have a negative effect on the dissipation of the impact load and knee joint stability due to these muscles acting too late, which may have contributed to the significantly higher F_V and LR F_V, and a lower net knee joint extension moment. It should be noted that although the participants maintained a similar lower limb muscle recruitment order, they may have displayed significant changes in the magnitude of the muscle activity with fatigue.

In contrast, during the vertical landing task, despite fatigue causing only minor changes to the kinetics and kinematics displayed by the participants, fatigue caused significant alterations in the lower limb muscle activation strategies the participants used. We speculate that later TA recruitment when fatigued during the vertical landing phase led to the higher plantar flexion velocity and less ankle plantar flexion at IC as participants had less time to achieve the same amount of plantar flexion as they achieved during the non-fatigued condition. Nevertheless, participants also displayed significantly later onset of BF and ST, and later peak BF, TA and MG activity during the vertical landing, which was not accompanied by any changes in the kinetic or kinematic data. It should be noted that these differences in muscle recruitment order displayed during the two landing phases are likely to have been moderated by the
preparation for the takeoff phase in the horizontal landing phase whereas there was no
follow-on movement after the vertical landing phase.

CONCLUSION

Fatigue of the SSC was found to decrease the $F_{PT}$ and LR $F_{PT}$ during the
horizontal landing phase but not the vertical landing phase of a stop-jump task in
asymptomatic athletes with normal patellar tendons. This reduction in patellar tendon
loading when fatigued was primarily attributed to the way the participants moderated
their landing technique, including significantly reducing their knee joint moment as a
consequence of using a smaller knee joint moment arm when landing with less knee
flexion and greater hip flexion, and less efficient utilization of the stretch-shortening
cycle during the horizontal landing phase. This decrease in patellar tendon loading
when fatigued, caused by altered landing technique during the horizontal landing phase,
may have a protective effect and potentially decrease the risk of developing patellar
tendon abnormalities and, in turn, patellar tendinopathy.

REFERENCES

1. Ostenberg A, & Roos H. Injury risk factors in female European football. A
   prospective study of 123 players during one season. Scandinavian Journal of

   football medical research programme: an audit of injuries in professional

   Impact of fatigue on gender-based high-risk landing strategies. Medicine &


Part III

Patellar Tendon Loading of Athletes with a Patellar Tendon Abnormality and How this is Moderated by Fatigue
Chapter 6

Landing Strategies of Athletes with an Asymptomatic Patellar Tendon Abnormality

This chapter is an amended version of the manuscript: Edwards S, Steele JR, McGhee DE, Beattie S, Purdam CR, Cook JL. Landing strategies of athletes with an asymptomatic patellar tendon abnormality. Medicine & Science in Sports & Exercise. 2010: 42(11); doi: 10.1249/MSS.0b013e3181e0550b.

ABSTRACT

Purpose

Risk factors associated with a clinical presentation of patellar tendinopathy are a patellar tendon ultrasonographic abnormality (PTA) and excessive loading caused by repetitive landing. It remains unknown whether characteristics of an athlete’s landing technique contribute to this excessive patellar tendon loading. This study investigated whether asymptomatic athletes with and without a PTA had different landing strategies and hypothesised that asymptomatic athletes with a PTA would create higher patellar tendon loading and a different lower limb landing strategy compared to athletes with normal patellar tendons.

Methods

Seven athletes with no previous history or clinical signs of patellar tendon injury with a PTA were matched to athletes with normal patellar tendons (controls). Participants performed five successful trials of a stop-jump task, which involved the simultaneous two-foot horizontal and then vertical landing. During each trial, the participants’ ground reaction forces and lower limb electromyographic data were
recorded, three-dimensional kinematics measured, and $F_{PT}$ calculated by dividing the net knee joint moment by the patellar tendon moment arm.

**Results**

Significant between-group differences in landing technique were mostly observed during the horizontal landing phase. Participants with a PTA created similar patellar tendon loading to the controls, but with altered sequencing, by landing with significantly greater knee flexion and extending their hips while the controls flexed their hips as they landed, reflecting, a different muscle recruitment order compared to the PTA group.

**Conclusions**

The crucial part in the development of PTA and, in turn, patellar tendinopathy, may not be the magnitude of the patellar tendon load but rather the loading patterns. This research provides clinicians with important landing assessment criteria against which to identify athletes at risk of developing patellar tendinopathy.

**INTRODUCTION**

Patellar tendinopathy is an overuse knee injury common in individuals who subject their extensor mechanism to intense and repetitive loading. Diagnosis of patellar tendinopathy is confirmed by a history of activity-related pain, focal tenderness, a Victorian Institute of Sport Assessment (VISA) score of less than 80 (1), and the presence of a patellar tendon ultrasonographic abnormality (PTA) (2) on diagnostic imaging. Interestingly, although PTA and tendon pain are the diagnostic criteria for patellar tendinopathy, PTA can also be evident in athletes without tendon pain, with a prevalence of 22%–32% (3-8). The presence of a PTA in asymptomatic athletes has been identified as a risk factor in the development of patellar tendinopathy (4, 7, 9), whereby the likelihood of an asymptomatic athlete with a PTA developing patellar
Part III: Chapter 6

tendinopathy increases four times in basketball players (4) and 17% in elite soccer players compared to asymptomatic athletes with no evidence of PTA (7). Despite being confirmed as a risk factor, the clinical importance of PTA changes has not yet been clarified (8) because an asymptomatic PTA can resolve, remain unchanged or worsen in athletes (5, 7) without predicting symptoms of patellar tendinopathy (3, 6, 8).

Altered lower limb landing strategies have also been associated with patellar tendinopathy (10-14). In symptomatic athletes with patellar tendinopathy, Richards et al. (10) observed that during a vertical landing, that these athletes landed with a higher rate of knee moment development, a relatively extended knee joint (10, 11), but attained a higher maximum knee flexion angle and a greater knee flexion range of motion. The authors claimed that greater maximum knee flexion during landing was a strong predictor of patellar tendinopathy (10), as increased knee flexion can increase the patellar tendon load and, in turn, contribute to development of patellar tendinopathy (10, 11). Nevertheless, Bisseling et al. (12) observed that symptomatic athletes with patellar tendinopathy used a ‘load avoiding’ landing strategy during a vertical landing task. That is, relative to control athletes, symptomatic athletes displayed a significantly lower knee joint moment, work and power despite no significant differences in peak vertical ground reaction force or loading rate (12). The researchers, however, did not explain how the symptomatic athletes achieved this reduction in load. It was also found that during a vertical landing task, asymptomatic athletes with a previous history of patellar tendinopathy task landed with a higher knee angular velocity and rate of knee moment development relative to athletes with no history of patellar tendon pain (12, 13). It remains unknown, however, whether the presence of PTA in asymptomatic athletes affects their landing technique or whether their landing technique might predispose them to developing a PTA and/or patellar tendinopathy. In addition, most of this
previous research examining the landing of athletes with patellar tendinopathy has investigated a vertical landing task (10, 12, 13, 15). However, a horizontal landing when compared to a vertical landing places the highest load on the patellar tendon, and should be preferably used when investigating lower-limb landing mechanics in athletes with patellar tendinopathy (16).

The purpose of this study was to identify whether asymptomatic athletes with a PTA displayed a different landing technique compared to athletes with a normal patellar tendon. It was hypothesised that asymptomatic athletes with a PTA would create higher patellar tendon loading and a different lower limb landing strategy compared to athletes with normal patellar tendons.

METHODS

Participants

Twenty-three skilled male athletes (mean age = 23.7 ± 4.0 years; height = 183.0 ± 6.2 cm; mass = 82.4 ± 10.4 kg) were recruited from team sports involving repetitive landing. All participants were right leg dominant, based on their preferred kicking leg (17). Participants reported no history of traumatic lower limb injuries. The patellar tendon morphology of all participants were documented by an experienced musculoskeletal sonographer (S.B.) using a 13 MHz linear array ultrasound transducer (Antares, Siemens AG, Germany) and the presence of an ultrasound abnormality, as defined by Cook et al. (9), was recorded.

Seven male participants with a PTA (Table 1) but no previous history or clinical signs of patellar tendinopathy (mean age = 25.2 ± 4.7 years; height = 183.4 ± 7.2 cm; mass = 83.2 ± 9.0 kg; VISA score = 96 ± 8; static dorsiflexion lunge test (18), range of motion = 13.9 ± 3.1 cm) were identified and individually matched for height, mass and test limb to seven male participants with normal patellar tendons (controls; age = 22.3 ±
2.4 years; height = 185.9 ± 8.1 cm; mass = 82.0 ± 12.6 kg; VISA score = 99 ± 2; static dorsiflexion lunge test range of motion = 15.5 ± 4.1 cm). If a participant had bilateral PTA, the lower limb with the larger PTA area was selected for analysis. All between-group comparisons were made with independent samples t-tests and there were no significant between-group differences in age, height, mass, static dorsiflexion range or VISA score. Written informed consent was obtained from each participant before data collection and all the study’s methods were approved by the institution’s Human Research Ethics Committee (HE06/205).

Table 3. PTA measurements in PTA Participants.

<table>
<thead>
<tr>
<th>Measurement (mm)</th>
<th>PTA Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sagittal plane height</td>
<td>3.3 ± 2.7 (1.4-8.8)</td>
</tr>
<tr>
<td>Axial plane height</td>
<td>3.3 ± 2.6 (1.2-9.6)</td>
</tr>
<tr>
<td>Axial plane width</td>
<td>6.6 ± 3.2 (3.2-11.9)</td>
</tr>
</tbody>
</table>

Values are presented as mean ± SD (range).

Experimental Task

A stop-jump was chosen as the experimental task as it places large loads on the patellar tendon during landing and involves two landing phases, a horizontal landing phase and a vertical landing phase (16). The horizontal landing phase required the participants to accelerate forwards for four steps towards two force platforms, to stop and perform the simultaneous two-foot landing with each foot contacting a separate force platform. The vertical landing phase immediately followed and required the participants to jump vertically upwards to strike a ball suspended from the ceiling and to then perform the simultaneous two-foot landing a second time with each foot again contacting a separate force platform. During the stop-jump task familiarisation, the effort among the participants at which they performed the task was standardised by using a set starting position before the force platform. The participants’ average
approach speed was measured immediately before the horizontal landing phase using infrared timing lights (OnSpot, University of Wollongong, Australia) and was similar in both participant groups (controls = 4.5 ± 0.5 m.s\(^{-1}\); PTA = 4.7 ± 1.0 m.s\(^{-1}\); \(p = 0.762\)). Both participant groups also achieved a consistent jump height prior to the vertical landing phase (controls = 50.5 ± 5.9 cm; PTA = 52.0 ± 6.0 cm; \(p = 0.646\)). Jump height effort was standardised among the participants by positioning the ball at the maximum height that each participant could touch the ball with both hands after performing the stop-jump movement. Each participant’s height, body mass, lower-limb dimensions and static ankle dorsiflexion lunge test range of motion (18) were measured before performing the stop-jump task.

**Experimental Procedure**

After completing a standardised 5- to 10-min warm-up of cycling on an ergometer (Monark Model 818E, Sweden), each participant was familiarised with the stop-jump task before performing at least five successful stop-jump trials, whereby a successful trial was defined as a participant placing each foot wholly on a separate force platform during both landing phases and contacting the suspended ball with both hands. During each trial the ground reaction forces generated at landing were recorded (1000 Hz) using two multichannel force platforms (Type 9281B; Type 9253B; Kistler, Winterthur, Switzerland) embedded in the floor, with each platform connected to a multichannel charge amplifier (Type 9865A; Type, 9865B; Kistler, Winterthur, Switzerland). The participant’s three-dimensional lower limb motion was recorded (100 Hz) using an OPTOTRAK® 3020 motion analysis system (Northern Digital, Waterloo, Canada). Infrared light-emitting diodes were placed on each participant’s dominant lower-limb and pelvis, on the shoe at the first and fifth metatarsal head and mid-anterior foot, lateral malleolus, medial malleolus, lateral leg, anterior distal leg.
anterior proximal leg, lateral femoral epicondyle, medial femoral epicondyle, lateral femur, anterior distal femur, anterior proximal femur, greater trochanter, anterior superior iliac spine, and iliac crest. To avoid losing view of the infrared light-emitting diodes, the participants wore minimal clothing, a t-shirt and shorts. Socks and sports shoes were worn during the stop-jump to minimise potential injury.

Electromyographic activity was recorded bilaterally for vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), tibialis anterior (TA), and medial gastrocnemius (MG) using two TeleMyo systems (Noraxon, Arizona, USA). After standard preparation (19), bipolar silver-silver-chloride surface electrodes (Ambu® Blue Sensor M, electrode size = 40.8 x 32 mm, detection area = 13.2 mm) were placed longitudinally on each muscle belly (inter-electrode distance of 20 mm). A common reference electrode was located on the tibial tuberosity of each lower limb. The EMG signals for each lower limb were sampled (1000 Hz, bandwidth 16-500 Hz) and relayed from two TeleMyo 900 battery powered transmitters (Noraxon, Scottsdale, Arizona, USA), firmly fixed around the participant’s waist, to two TeleMyo 900 receivers. The kinetic, kinematic and electromyographic data were time synchronised and collected using First Principles software (Version 1.00.2, Northern Digital, Waterloo, Canada).

Data Reduction

Analysis of the kinematic and kinetic data was performed using Visual 3D software (Version 3, C-Motion, Germantown, MD). The raw ground reaction force data were initially filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter \( (f_c = 50 \text{ Hz}) \) before calculating the ground reaction force variables (20). The raw kinematic coordinates, the ground reaction forces, the free moments and the center of pressure data were then filtered using a fourth-order zero-phase-shift Butterworth digital
low pass filter ($f_c = 18$ Hz) before calculating individual joint kinematics, knee joint moments and patellar tendon forces (20). The patellar tendon forces were calculated by dividing the knee joint moment by the patellar tendon moment arm (21). Patellar tendon moment arms were calculated as a function of knee joint angle using the method of Herzog & Read (22).

The raw EMG signals were filtered using a fourth order zero-phase shift Butterworth (high-pass $f_c = 15$ Hz) to eliminate any movement artefact. To quantify temporal characteristics of the muscle bursts, the filtered EMG data were full-wave rectified with a $20$ Hz low pass filter to create linear envelopes that were then screened using a threshold detector (8% of the maximum amplitude) (23) using customized LabVIEW software (LabVIEW 8, National Instruments, Austin, TX). Each individual muscle’s filtered EMG signal was visually inspected to confirm the validity of the calculated results to minimise the probability of an error.

Data Analysis

The two landing phases within the stop-jump movement were then identified from the vertical ground reaction force-time curve as (i) the “horizontal” landing phase and (ii) the “vertical” landing phase. The primary outcome variable analysed during these two landing phases was the peak patellar tendon force ($F_{PT}$). Secondary variables analysed during the same two landing phases included the peak vertical ground reaction force ($F_V$); the ankle, knee and hip joint kinematics; and the time of the onset and peak muscle activity of each of the seven lower limb muscles relative to the time of the $F_{PT}$ in each landing phase. Loading rate of the $F_V$ (LR $F_V$, body weight per second) was calculated by dividing the $F_V$ by the time interval between the initial foot-ground contact (IC) to the time of the $F_V$. Loading rate of the $F_{PT}$ (LR $F_{PT}$, body weight per second) was calculated by dividing the $F_{PT}$ by the time interval between IC to the time
of the $F_{PT}$. The temporal events (IC, $F_V$ and $F_{AP}$) were defined using the 18-Hz filtered kinetic data, with initial contact defined when the vertical ground reaction force exceeded 30 N. The jump height attained by each participant during the stop-jump movement was defined as the difference in the maximum vertical displacement of the greater trochanter marker minus the vertical displacement of the same marker measured while each participant stood motionless.

**Statistics Analysis**

Means and SD were calculated for each kinetic, kinematic and muscle activity variable for the participants with PTA and their counterparts with normal patellar tendons (controls) during the horizontal and vertical landing phases of the stop-jump task. After confirming normality and equal variance, the data were analysed using a series of independent samples $t$-tests to determine whether there was any significant differences ($P < 0.05$) in the primary and secondary outcome variables during the two landing phases of the stop-jump task between the two participant groups. Although multiple statistical tests were conducted, increasing the chance of incurring an error, no adjustment to the alpha level was deemed necessary given the exploratory nature of the study and the low cost associated with incurring a Type I error. All statistical procedures were conducted using the Statistical Package for the Social Sciences (Version 15, SPSS Inc., Chicago, IL).

**RESULTS**

**Patellar Tendon Loading**

The PTA and control groups generated a similar mean $F_{PT}$, $F_{PT}$ loading rate and the duration from IC to the time of the $F_{PT}$ during the horizontal and vertical landing phases of the stop-jump task (Figure 19).
Figure 19. Mean (SD) values of the peak patellar tendon forces and the peak vertical ground reaction forces (normalised to body weight) generated by the PTA group and the controls during (1) the horizontal and (2) the vertical landing phases of a stop-jump task. $F_V$, peak vertical ground reaction force; $F_{AP}$, peak anterior-posterior ground reaction force; $F_{PT}$, peak patellar tendon forces; $LR_{FV}$, loading rate of the $F_V$; $LR_{FPT}$, loading rate of the $F_{PT}$; IC-$F_V$, initial foot-ground contact (IC) to the time of the $F_V$; IC-$F_{PT}$, time from IC to the time of the $F_{PT}$. *Indicates a significant difference ($P < 0.05$) between the two participant groups.
**Ground Reaction Forces**

During the horizontal landing phase of the stop-jump task, there was no significant between-group difference in the $F_V$, $F_V$ loading rate or the duration from IC to the time of the $F_V$ over which each group sustained these loads. However, during the vertical landing phase of the stop-jump task, the PTA group displayed a significantly lower $F_V$ loading rate than the controls ($P = 0.03$), although no significant difference was found between groups in the $F_V$ or the duration from IC to the time of the $F_V$ (Figure 19).

**Joint Kinematic Data**

During the horizontal landing phase, compared to the controls, the PTA group landed with significantly greater knee flexion ($P = 0.05$) and a slower knee flexion velocity at IC ($P = 0.05$), then displayed greater internal knee rotation at the time of the $F_V$ ($P = 0.04$), and continued to display a slower knee flexion velocity at the time of the $F_{PT}$ ($P = 0.01$). The PTA group also displayed significantly less knee flexion ROM from the time of IC to the time of $F_{PT}$ compared to the controls (PTA = $36 \pm 11^\circ$; controls = $50 \pm 9^\circ$; $P = 0.03$). Relative to the controls, the PTA group utilised a very different hip movement strategy when landing, whereby they initially displayed a strong trend for greater hip flexion at IC ($P = 0.06$) but then extended, not flexed, their hips, displaying significantly faster hip extension velocity at IC ($P = 0.05$), a greater hip adduction angle at the time of the $F_V$ ($P = 0.01$), and faster hip external rotation velocity at the time of the $F_{PT}$ ($P = 0.03$; Figure 20 and Figure 21).

During the vertical landing phase, the PTA group landed with significantly greater ankle inversion at the time of the $F_{PT}$ ($P = 0.04$) and faster hip flexion velocity at the time of the $F_V$ ($P = 0.05$) compared to the controls (Figure 20 and Figure 21). No
Figure 20. Means (SD) values of joint angles (°) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force ($F_V$) and at the time of the peak patellar tendon force ($F_{PT}$) during the two landing phases of the stop-jump task for the PTA and control groups. *Indicates a significant difference ($P < 0.05$) between the two participant groups.

Other lower limb landing technique differences were noted between the two participant groups during the vertical landing phase of the stop-jump task.

Muscle Activation Patterns

Although no significant between-group differences were found in the timing of the onset or peak muscle burst activity relative to the time of the $F_{PT}$ during the horizontal or vertical landing phases (Figure 22), differences were found in the muscle
Figure 21. Means (SD) values of joint velocities (°.s⁻¹) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force ($F_V$) and at the time of the peak patellar tendon force ($F_{PT}$) during the two landing phases of the stop-jump task for the PTA and control groups. *Indicates a significant difference ($P < 0.05$) between the two participant groups.

recruitment order. That is, during the horizontal landing phase, the controls recruited their lower leg muscles first (TA and MG), followed by the hamstring muscles (BF and ST), and finally the quadriceps muscles (VM, VL, and RF). In contrast, during the horizontal landing phase, the PTA group initially recruited their hamstring muscles (ST and BF), followed by the lower leg muscles (TA and MG), and lastly the quadriceps muscles (VM, RF, and VL). During the vertical landing phase, both groups initially recruited their MG, followed by the hamstring muscles (BF and ST). However, the
Figure 22. Means (SD) values for the times of (1) the onset of muscle activation and (2) the peak muscle activity relative to the time of the peak patellar tendon force ($F_{PT}$) generated during the horizontal (H) and vertical (V) landing phases of a stop-jump task for the PTA and control groups. VL, vastus lateralis; RF, rectus femoris; VM, vastus medialis; ST, semitendinosus; BF, biceps femoris; MG, medial gastrocnemius; TA, tibialis anterior.
controls then recruited TA and lastly the quadriceps muscles (RF, VM, and VL), whereas the PTA group recruited the quadriceps muscles (VM, VL, and RF) and finally TA (Table 4).

**Table 4.** Lower-limb muscle recruitment order relative to the time of $F_{PT}$ during the horizontal and vertical landing phases of a stop-jump task.

<table>
<thead>
<tr>
<th>Onset Order</th>
<th>Horizontal Landing Phase</th>
<th>Vertical Landing Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PTA ($n=7$)</td>
<td>Control ($n=7$)</td>
</tr>
<tr>
<td>1st</td>
<td>ST</td>
<td>TA</td>
</tr>
<tr>
<td>2nd</td>
<td>BF</td>
<td>MG</td>
</tr>
<tr>
<td>3rd</td>
<td>TA</td>
<td>BF</td>
</tr>
<tr>
<td>4th</td>
<td>MG</td>
<td>ST</td>
</tr>
<tr>
<td>5th</td>
<td>VM</td>
<td>VL</td>
</tr>
<tr>
<td>6th</td>
<td>VL</td>
<td>VM</td>
</tr>
<tr>
<td>7th</td>
<td>RF</td>
<td>RF</td>
</tr>
</tbody>
</table>

= Hamstring muscles (biceps femoris (BF); semitendinosus (ST))

= Quadriceps muscles (vastus medialis (VM); rectus Femoris (RF); vastus lateralis (VL))

= Lower leg muscles (medial gastrocnemius (MG); tibialis anterior (TA))

The order of muscle recruitment was based on the mean muscle activity onset time for each of the seven lower limb muscles relative to the time of the $F_{PT}$ in each landing phase.

**DISCUSSION**

Although asymptomatic athletes with a PTA have an increased risk of developing patellar tendinopathy (4, 7, 9), the clinical relationship of the PTA to lower-limb landing mechanics has not been previously investigated. The results of this study partially support the hypothesis that asymptomatic athletes with a PTA utilise a different lower-limb landing strategy compared to athletes with normal patellar tendons. Interestingly, this hypothesis was only supported during the horizontal landing phase of the stop-jump task, whereas the two participant groups displayed similar patellar tendon loading and a similar landing strategy during the vertical landing phase of the stop-jump task.
Most previous biomechanics research examining the landing of athletes with patellar tendinopathy has focused on tasks that involve a vertical landing phase (10, 12, 13, 15). That is, during vertical landing tasks, previous research has reported that landing with less knee flexion at IC (10), greater knee flexion at the time of the $F_V$ (12, 13), greater maximum knee flexion angle (10), higher knee flexion velocity (12-14) and/or knee flexion moment (10, 12, 13) are associated with patellar tendinopathy. However, athletes use a different landing movement strategy during the horizontal landing phase of a stop-jump movement compared to the vertical landing phase (16). We speculate that the greater between-group differences in landing technique observed during the horizontal landing phase relative to the vertical landing phase may be due to the horizontal landing task requiring greater musculoskeletal control to decelerate the lower limbs while dissipating higher patellar tendon loads. The results of this study also support the notion that research investigating lower-limb landing mechanics and the risk factors for developing patellar tendinopathy should incorporate a dynamic horizontal landing task (16). This should ensure that athletes who are at an increased risk of developing a PTA and, in turn, patellar tendinopathy are identified. Given that most between-group significant differences in the present study were evident during the horizontal landing phase, the following discussion will focus only on this component of the experimental task.

Interestingly, the PTA group generated similar $F_{PT}$ and $F_V$ when landing in the horizontal phase compared to their control counterparts, suggesting that the PTA group did not use a force reduction strategy when landing. Instead, the PTA group appeared to modify their lower-limb kinematics and muscle recruitment order relative to the control group.
Part III: Chapter 6

It has been suggested that reduced ankle dorsiflexion range may increase the risk of developing patellar tendinopathy (24) by limiting the range of motion over which the ankle joint plantar flexor muscles can act, thereby causing the knee and hip joints to have to contribute more to force dissipation during landing (25). In contrast to this previous research, the current study found no significant between-group differences in ankle angles, range of motion or velocities during the stop-jump task or static ankle dorsiflexion lunge test range of motion.

Participants in the PTA group during a horizontal landing phase displayed greater knee flexion angles at IC and at the time of the $F_V$ combined with a slower rate of knee flexion and less knee flexion range of motion from the time of IC to the time of the $F_{PT}$ than the controls. The compressive force and mechanical stress acting on the patella and patellar tendon (26) have been found to be greater at higher knee flexion angles, and are asymmetrically distributed to be higher on the medial section of the patellar tendon (26, 27). Therefore, it may not be the magnitude of the load that the patellar tendon sustains that is crucial to the development of PTA. Instead, we speculate that the direction of this load and the unique nature of the patellofemoral articulation is more important, as proximal patellar tendinopathy is thought to be associated with some compressive load in addition to the tensile loads acting on the patellar tendon, which may result in histological adaptation towards a compression resistant morphology (28). This notion is reinforced by the location of the PTA occurring in the mid or medial part of the proximal patellar tendon, which is in agreement with previous research (3, 29). Furthermore, the greater knee abduction and significantly greater knee internal rotation displayed by the PTA group relative to their control counterparts, suggests a mechanism for increased load on the medial and mid section of the proximal part of the patellar
tendon and that the PTA group had a poor ability to control their knee joint posture during landing.

Despite lumbopelvic control being considered a vital component of clinical rehabilitation programs for patellar tendinopathy, no previous research has confirmed its importance (30). During the horizontal landing phase, the PTA group utilised a hip movement strategy that was different to the strategy used by the control group. That is, the PTA participants landed in greater hip flexion at IC, and then extended their hips throughout the landing action. The controls, in contrast, landed in less hip flexion and flexed their hips as they landed. The greater hip flexion angle displayed by the PTA group at IC would position their centre of mass more posteriorly relative to their base of support, necessitating greater forward translation of the centre of mass during the landing phase. This, together with the greater knee flexion, may further increase the tensile and compressive loads on the proximal part of the patellar tendon and contribute to development of PTA.

Although there were no significant differences in the onset or timing of the peak muscle burst activity relative to the time of the $F_{PT}$ during the horizontal landing phase, the two participant groups displayed a different muscle recruitment order. Earlier recruitment of the hamstrings by the PTA group, particularly the medial hamstrings (ST), occurred when the participants’ centres of mass were located posteriorly relative to their base of support. As such, we speculate that this earlier recruitment of the biarticular hamstring muscles also helped to stabilise the torso during landing via their action at the hip joint. Furthermore, the line of action of the hamstring muscles displayed by the PTA group during landing will create a greater posterior shear and compressive force at the knee joint and increase the demand on the knee extensor muscles, relative to the control group. This, together with earlier VM onset, which
attaches to the medial aspect of the patellar tendon, suggests greater compression of the medial posterior aspect of the patellar tendon, which is a primary area where a PTA develops (2, 3, 29, 31). The relatively more lengthened position of the quadriceps muscle as a consequence of the higher knee flexion angle displayed by the PTA group may also contribute to patellar tendon compression via greater tensile loading of the superficial fibres of the patellar tendon on the anterior surface of the patella (32) and via a higher quadriceps tendon force-to-patellar tendon force ratio (33, 34). The distribution of force through the patella and patellar tendon has been found to be asymmetrically concentrated and greater medially (26, 27), which corresponds to the area most vulnerable to patellar tendinopathy (2, 3, 29). This suggests that the site of maximum stress is affected by the relative pull of VM (26) and that muscle dysfunction, which was evident in the PTA group in this study, may be a primary causative agent in the aetiology of patellar tendinopathy. Lastly, we speculate that due to the later TA activation evident in the PTA group relative to their control counterparts, the dorsiflexion that occurred during landing was not initiated by leg muscle activation, but rather the greater forward translation of the centre of mass as the participants initially contacted the ground with their rearfoot.

Interestingly, most of the between-group differences in lower-limb landing strategy primarily occurred in the sagittal plane during the horizontal landing task. That is, the PTA group landed with greater knee and hip flexion, and extended their hips as they landed during the horizontal landing phase. These biomechanical characteristics are relatively simple to observe, providing clinicians with possible criteria to identify athletes who might be at risk of developing a PTA and, in turn, patellar tendinopathy. It also provides clinicians with a framework to assess and manage lower-limb landing
strategies in athletes with patellar tendinopathy, as changes in joint angle can be achieved through simple verbal instruction (35).

We acknowledge that potential between-group differences in landing technique may have been masked in the present study by the small participant number in each group and high variability, as reflected by the high SD, particularly in the hip kinematic and electromyographic data. However, the large standard deviations may also reflect individual variations in landing strategies, which have been confirmed in numerous landing studies (36, 37). The inclusion of both unilateral and bilateral PTA participants within the PTA group may have also influenced the results as the aetiology of bilateral patellar tendinopathy is thought to be different from the aetiology of unilateral patellar tendinopathy (38, 39), such that these subgroups may need to be treated separately (39), although this is yet to be confirmed. We also acknowledge that there are limitations when using a two-dimensional model to estimate patellar tendon force as the patellar tendon is considered to be a three-dimensional structure and that the net knee joint moment was used to estimate patellar tendon force, which may have lead to an underestimation of the patellar tendon force.

CONCLUSION

During the horizontal landing phase of a stop jump task asymptomatic athletes with a PTA displayed a different landing strategy compared to their counterparts with normal patellar tendons by contacting the ground with greater knee flexion and then extending rather than flexing their hips throughout the horizontal landing action, although both participant groups generated similar patellar tendon loading. We speculate that it may not be the magnitude of the load that the patellar tendon sustains that is crucial to the development of PTA but rather the direction of this load, caused by differences in landing kinematics, and the unique nature of the patellofemoral
articulation that are more important. As the differences in landing displayed by asymptomatic athletes with a PTA primarily occurred in the sagittal plane, these biomechanical characteristics provide clinicians with important landing assessment criteria against which to identify athletes at risk of developing a PTA and, in turn, patellar tendinopathy.

REFERENCES


38. Gaida JE, Cook JL, Bass SL, Austen S, Kiss ZS. Are unilateral and bilateral patellar tendinopathy distinguished by differences in anthropometry, body

Chapter 7

Asymptomatic Athletes with a Patellar Tendon Abnormality do not Adapt when Fatigued


ABSTRACT

Objective

Although muscle fatigue is a risk factor for developing knee injuries, healthy athletes alter their landing technique when fatigued, possibly as a protective effect to decrease the risk of developing patellar tendinopathy. This study’s purpose was to investigate the effect of muscle fatigue on the landing technique and patellar tendon loads generated by asymptomatic athletes with a patellar tendon abnormality (PTA) during a stop-jump movement.

Methods

Seven asymptomatic athletes with a PTA performed repeated trials of a stop-jump task, before and after the fatigue protocol, which involved participants repeatedly performing sets of 30 submaximal rebound exercises on a sledge apparatus followed by 30 seconds rest. During each stop-jump trial, the participants’ ground reaction forces and electromyographic data were recorded, three-dimensional kinematics measured, and peak patellar tendon force ($F_{PT}$) calculated by dividing the net knee joint moment by the patellar tendon moment arm.
Results

Compared to the non-fatigued condition, participants during the horizontal landing phase only displayed a significantly higher LR FV and less hip flexion at IC. During the vertical landing phase when fatigued, participants displayed significantly higher LR FV, less hip external rotation and slower knee flexion velocity at IC, and a later onset of BF muscle activity relative to the time of F_{PT}.

Conclusion

Asymptomatic PTA participants did not substantially modify their landing technique or patellar tendon loads during a stop-jump movement in response to muscle fatigue. We speculate that these athletes may not be capable of sufficient movement variability in their lower limb landing strategies to respond to muscle fatigue.

INTRODUCTION

Repetitive landing is a crucial factor in the development of the overuse injury patellar tendinopathy (1-5). Landing mechanics may also be critical, as numerous studies have shown that athletes suffering patellar tendinopathy display altered lower limb landing technique relative to their uninjured counterparts (2, 6-10). It is thought that these technique modifications contribute to the development of patellar tendinopathy via increasing the magnitude of the patellar tendon load (2, 6). It has been unclear, however, whether these technique alterations were the cause of or affected by the pain associated with patellar tendinopathy.

The presence of a patellar tendon ultrasonographic abnormality (PTA) (11, 12), which can be evident in athletes with or without tendon pain, is also a risk factor for patellar tendinopathy (11-16). Our recent research that investigated the landing technique of athletes with an asymptomatic PTA revealed that their technique during the horizontal landing phase of a stop-jump movement was different to the technique of
uninjured matched controls with normal patellar tendons (10). Athletes with a PTA displayed greater knee flexion together with a hip extension strategy, as opposed to a hip flexion strategy characteristic of control athletes (10). We speculated that these technique modifications evident in this asymptomatic PTA cohort may have contributed to the development of their PTA (10). Furthermore, we suggested that the patellar tendon loading direction caused by differences in their landing kinematics, rather than the magnitude of the patellar tendon load, may be the critical factor in the development of patellar tendinopathy, as the asymptomatic athletes with a PTA generated similar patellar tendon loads during the horizontal landing task compared to healthy athletes with normal tendons (10).

Altered lower limb landing technique has also been observed in healthy athletes as a consequence of muscle fatigue (17-19). Although muscle fatigue is thought to be a major risk factor in the development of knee joint injuries (17, 19-21), our recent research showed that healthy fatigued athletes generated lower patellar tendon loads during the horizontal landing phase of a stop-jump task compared to when they were not fatigued (22). This modification to their landing technique in response to muscle fatigue may have a protective effect and potentially decrease the risk of developing a PTA and, in turn, patellar tendinopathy (22). Whether asymptomatic athletes with a PTA can alter their magnitude and/or pattern of patellar tendon loading, and modify their landing technique in response to muscle fatigue is unknown.

This study aimed to investigate the effect of muscle fatigue on the landing technique and patellar tendon loads generated by asymptomatic athletes with a PTA during the horizontal and vertical landing phases of a stop-jump movement. It was hypothesised that in response to muscle fatigue, asymptomatic athletes with a PTA would decrease the magnitude and alter the direction of patellar tendon loading by
modifying their landing technique during the horizontal landing phase of the stop-jump task.

**METHODS**

**Participants**

Seven participants (mean age = 25.2 ± 4.7 years; height = 183.4 ± 7.2 cm; mass = 83.2 ± 9.0 kg; VISA score = 96 ± 8; static dorsiflexion lunge test (23) range of motion = 13.9 ± 3.1 cm) were identified as having a PTA (24) by an experienced musculoskeletal sonographer (S.B.) using a 13 MHz linear array ultrasound transducer (Antares, Siemens AG, Germany). The participants reported no previous history or clinical signs of patellar tendinopathy. If a participant had bilateral PTA, the lower limb with the larger PTA area was selected for analysis. All participants were right leg dominant, based on their preferred kicking leg (25). Written informed consent was obtained from each participant and the study was approved by the University of Wollongong Human Research Ethics Committee (HE06/205).

**Experimental Protocol**

No less than one week prior to data collection, participants performed a familiarisation session of the study protocol, which included a standardised 5-10 minute warm-up of cycling on an ergometer (Monark Model 818E, Sweden), a familiarisation of the stop-jump task (described below), before performing a full trial of the fatigue protocol to a fatigued state (26). The participants then returned to the Biomechanics Research Laboratory on a second occasion for data to be collected during the full experimental protocol, which involved the warm-up followed by standardised trials of the stop-jump task both before and after performing the fatigue protocol (22).
Experimental Task

A stop-jump movement, consisting of a horizontal landing phase, which was immediately followed by a vertical landing phase, was chosen as the experimental task as it places large loads on the patellar tendon during landing (27). The horizontal landing phase required the participants to accelerate forwards for four steps towards two force platforms, to stop and perform the simultaneous two-foot landing with their right and left feet contacting separate force platforms. The vertical landing phase immediately followed and required the participants to jump vertically upwards to strike a ball suspended from the ceiling and to then perform the simultaneous two-foot landing a second time with each foot again contacting separate force platforms. During the stop-jump task familiarisation, the effort among the participants at which they performed the task was standardised by using a set starting position away from the force platform. The participants’ average approach speed was measured immediately before the preparation phase of the first landing using infrared timing lights (OnSpot, University of Wollongong). Jump height effort was standardised among the participants by positioning the ball at the maximum height each participant could touch the ball with both hands after performing the stop-jump movement during task familiarisation. Before performing the stop-jump task, each participant’s static ankle dorsiflexion lunge test range of motion (23), height, body mass and lower limb dimensions were evaluated as descriptive characteristics of the participant cohort.

Fatigue Protocol

The protocol utilised to induce lower limb muscle fatigue, which has previously been found to be valid and reliable, is described in detail elsewhere (26). In brief, it required the participants to repeatedly perform sets of 30 submaximal rebound exercises on a sledge apparatus immediately followed by 30 seconds rest. Muscle fatigue was
deemed when the participant could no longer reach 70% of their maximal rebound height for three out of five rebound exercises or when participants self terminated the sets as they felt that they could no longer continue. An increase in post-fatigue blood lactate level of at least 6 mmol/L, analysed using an Accusport blood lactate analyser (Boehringer Mannheim, Germany), was also measured at the end of the experimental protocol to confirm muscle fatigue.

**Experimental Procedures**

During each stop-jump trial the ground reaction forces generated during each landing were recorded (1000 Hz) using two multichannel force platforms (Type 9281B; Type 9253B; Kistler, Winterthur, Switzerland) embedded in the floor, with each platform connected to a multichannel charge amplifier (Type 9865A; Type, 9865B; Kistler, Winterthur, Switzerland). The participant’s three-dimensional lower limb motion was recorded (100 Hz) using an OPTOTRAK® 3020 motion analysis system (Northern Digital, Waterloo, Canada). Infrared light-emitting diodes were placed on each participant’s dominant lower limb and pelvis, on the shoe at the first and fifth metatarsal head and mid-anterior foot, lateral malleolus, medial malleolus, lateral leg, anterior distal leg, anterior proximal leg, lateral femoral epicondyle, medial femoral epicondyle, lateral femur, anterior distal femur, anterior proximal femur, greater trochanter, anterior superior iliac spine and iliac crest. To avoid losing view of the infrared light-emitting diodes, the participants wore minimal clothing (a t-shirt and shorts). Socks and sports shoes were worn during the stop-jump.

Electromyographic activity was recorded bilaterally for vastus lateralis (VL), rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), tibialis anterior (TA), and medial gastrocnemius (MG) using two TeleMyo systems (Noraxon, Arizona, USA). Following standard preparation (28), bipolar silver-silver-
chloride surface electrodes (Ambu® Blue Sensor M, electrode size = 40.8 x 32 mm, detection area = 13.2 mm²) were placed longitudinally on each muscle belly (inter-electrode distance of 20 mm). A common reference electrode was located on the tibial tuberosity of each lower limb. The electromyographic signals for each lower limb were sampled (1000 Hz, bandwidth 16-500 Hz) and relayed from two TeleMyo 900 battery powered transmitters (Noraxon, Arizona, USA), firmly fixed around the participant’s waist, to two TeleMyo 900 receivers. The kinetic, kinematic and electromyographic data were time synchronised and collected using First Principles software (Version 1.00.2, Northern Digital, Waterloo, Canada).

Data Reduction

Analysis of the kinematic and kinetic data was performed using Visual 3D software (Version 3, C-Motion, Maryland, USA). The raw ground reaction force data were initially filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter ($f_c = 50$ Hz) before calculating the ground reaction force variables. The raw kinematic coordinates, ground reaction forces, free moments and center of pressure data were then filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter ($f_c = 18$ Hz) before calculating individual joint kinematics, internal knee joint moments and patellar tendon forces (19, 29). The patellar tendon forces were calculated by dividing the net knee joint moment by the patellar tendon moment arm (30). Patellar tendon moment arms were calculated as a function of knee joint angle using the method of Herzog & Read (31).

The raw electromyographic signals were filtered using a fourth-order zero-phase shift Butterworth filter (high-pass $f_c = 15$ Hz) to eliminate any movement artefact. To quantify temporal characteristics of the muscle bursts, the filtered electromyographic data were full-wave rectified, filtered with a 20 Hz low pass filter and then full-wave
rectified to create linear envelopes that were then screened using a threshold detector (8\% of the maximum amplitude) (32) using customised software (LabVIEW 8, National Instruments). Each individual muscle’s filtered signal was visually inspected to confirm the validity of the calculated results of the temporal characteristics of the muscle bursts to minimise the probability of error.

**Data Analysis**

The two landing phases within the stop-jump movement were firstly identified from the vertical ground reaction force trace: (i) the “horizontal” landing phase and (ii) the “vertical” landing phase (27). The primary outcome variable analysed during these two landing phases was the peak patellar tendon force ($F_{PT}$). Secondary variables analysed during the same two landing phases included the peak vertical ground reaction force ($F_V$) and peak anterior-posterior ground reaction force ($F_{AP}$); ankle, knee and hip joint kinematics; the peak knee joint moment; and the time of the onset and peak activity of each of the seven lower limb muscles relative to the time of the $F_{PT}$ in both landing phases. Loading rate of the $F_V$ ($LR_{F_V}, BW.s^{-1}$) was calculated by dividing the $F_V$ by the time interval between initial foot-ground contact (IC) to the time of the $F_V$. Loading rate of the $F_{PT}$ ($LR_{F_{PT}}, BW.s^{-1}$) was calculated by dividing the $F_{PT}$ by the time interval between IC to the time of the $F_{PT}$. The temporal events (IC, and at the time of the peak $F_V$ and $F_{AP}$) were defined using the 18 Hz filtered kinetic data, with initial contact defined when the ground reaction force exceeded 30 N. The jump height (cm) attained by each participant during the stop-jump movement was also calculated as the difference in the maximum vertical displacement of the greater trochanter marker minus the vertical displacement of the same marker measured while each participant stood motionless.
Statistical Analysis

Means and standard deviations were calculated for each kinetic, kinematic and muscle activity variable displayed by the participant cohort during the horizontal and vertical landing phases in the non-fatigued (NF) and fatigued (F) condition. After confirming normality and equal variance, the data were analysed using paired t-tests to determine whether there were any significant differences \((p < 0.05)\) in the primary and secondary outcome variables between the two fatigue conditions. All statistical procedures were conducted using SPSS Statistical Software (Version 15, SPSS Inc., Chicago, USA).

RESULTS

Fatigue Variables

During the fatigue protocol, participants performed on average 14.0 ± 8.7 fatigue sets and displayed a significant increase in post-fatigue blood lactate level above the 6 mmol/L fatigue criterion (NF = 3.2 ± 0.6 mmol/L; F = 7.1 ± 2.1 mmol/L; \(t = -6.92; p < 0.00\)). It should be noted, however, that some participants did not achieve both fatigue criteria as either they were physically unable to perform another SSC set and self-terminated the fatigue protocol or there was a delay in obtaining the post-fatigue blood lactate sample.

Despite standardising the stop-jump task to reduce the effects of fatigue decreasing approach velocity and vertical jump height during the stop-jump task, fatigue lead to a significant decrease in the participants’ average approach speed (NF = 4.7 ± 1.0 m/s; F = 4.4 ± 1.0 m/s; \(t = 3.072; p < 0.022\)) and the average vertical jump height attained (NF = 51 ± 6 cm; F = 46 ± 6 cm; \(t = 3.856; p = 0.012\)).
Part III: Chapter 7

Patellar Tendon Loading & Ground Reaction Forces

During both the horizontal and vertical landing phase of the stop-jump movement, there were no significant between-fatigue condition differences in patellar tendon loading or peak net knee joint extension moment. Furthermore, the only

Horizontal Landing

Vertical Landing

Figure 23. Mean (± SD) of the forces generated during the horizontal and vertical landing phases of a stop-jump task (normalised to body weight) of 7 asymptomatic male athletes with a PTA. (A) Peak vertical ground reaction force (F_v), peak anterior-posterior ground reaction force (F_AP), peak patellar tendon forces (F_PT) and peak net knee joint extension moment. (B) The loading rate of the F_v (LR F_v) and the loading rate of the F_PT (LR F_PT). (C) The time from initial foot-ground contact (IC) to the time of the F_v (IC to F_v), the time from IC to the time of the F_AP (IC to F_AP) and the time from IC to the time of the F_PT (IC to F_PT). *Indicates a significant between-fatigue condition difference (p < 0.05).
significant between-fatigue condition difference in the ground reaction force variables was a significantly higher LR F_V during the horizontal \((p = 0.022)\) and vertical \((p = 0.019)\) landing phase when the participants were fatigued compared to when non-fatigued (Figure 23).

**Joint Kinematic Data**

The asymptomatic PTA participants displayed similar ankle, knee and hip joint positions and velocities from IC to the time of the F_PT during both fatigue conditions (Figure 24 and Figure 25). The only significant between-fatigue condition differences

![Figure 24](image.png)

**Figure 24.** Means \((\pm SD)\) of joint angles \((^\circ)\) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force \((F_V)\) and at the time of the peak patellar tendon force \((F_PT)\) during the two landing phases of the stop-jump task of 7 asymptomatic male participants with a PTA. *Indicates a significant between-fatigue condition difference \((p < 0.05)\).
Figure 25. Means (± SD) of joint velocities (°.s⁻¹) displayed at initial foot-ground contact (IC), at the time of the peak vertical ground reaction force (Fᵥ) and at the time of the peak patellar tendon force (Fᴾ) during the two landing phases of the stop-jump task of 7 asymptomatic male participants with a PTA. *Indicates a significant between-fatigue condition difference (p < 0.05).

were less hip flexion at IC (p = 0.019) during the horizontal landing phase; and less hip external rotation at IC (p = 0.028) and slower knee flexion velocity at IC (p = 0.04) during the vertical landing phase in the fatigued condition compared to the non-fatigued condition.

**Muscle Activation Patterns**

The PTA participants used a relatively consistent muscle recruitment strategy to stabilize their lower limbs between-fatigue conditions for both the horizontal and
Figure 26. Mean (± SD) for the times of the (A) onset of muscle activation and (B) the peak muscle activity relative to the time of the peak patellar tendon force ($F_{PT}$) generated during the horizontal and vertical landing phases of a stop-jump movement during the non-fatigued and fatigued condition of 7 asymptomatic male participants with a PTA. Negative values indicate muscle activation variable occurred before $F_{PT}$; VL = vastus lateralis; RF = rectus femoris; VM = vastus medialis; ST = semitendinosus; BF = biceps femoris; MG = medial gastrocnemius; TA = tibialis anterior.
vertical landing phases. The only significant difference found was a significantly later onset of muscle burst activity for BF relative to the time of the $F_{PT}$ activity when the subjects were fatigued during the vertical landing phase compared to when non-fatigued ($p = 0.047$; Figure 26).

DISCUSSION

This is the first study to systematically investigate the effect of muscle fatigue on the landing technique and patellar tendon loads generated by asymptomatic athletes with a PTA during the horizontal and vertical landing phases of a stop-jump movement. As anticipated, fatigue caused very few changes to the participant’s technique during the vertical landing phase of the stop-jump movement. However, contrary to our hypothesis, this asymptomatic cohort of PTA participants also showed very few changes to their landing kinematics during the horizontal landing phase of the stop-jump task when fatigued. Consequently, there was not a significant change to the patellar tendon load generated during the horizontal landing phase by this sample of asymptomatic athletes with PTA in response to muscle fatigue. In contrast, healthy athletes with normal patellar tendons decrease the magnitude and alter the direction of their patellar tendon load, which leads to less compressive load on the patellar tendon, when fatigued during the horizontal landing phase of a stop-jump task compared to when they are not fatigued (22).

If asymptomatic athletes with a PTA do not alter either the magnitude or pattern of patellar tendon loading, or their landing strategy, they may be less able to adapt to changes evoked by muscle fatigue. We speculate that this reduced ability to adapt to changing conditions may be due to the asymptomatic athletes with a PTA having limited potential for movement variability, whereby movement variability refers to variations in motor performance across multiple repetitions of a task (33). Movement
variability has traditionally been treated as noise within data (34, 35) or to be an unimportant (35) or confounding issue for experimental design. More recent research, however, has suggested that movement variability is not only essential for functional adaptation to dynamic environments (36), but has also linked low movement variability with knee joint injuries (37) and overuse injuries (33, 35).

Movement variability is thought to allow better load distribution among different tissues (33, 35), different areas within the same tissue, or within the same tissue or location at different times (33). This may allow the detrimental effects of repetitive loading to be reduced by enabling longer adaptation time for tissues between loading events (33). Therefore, movement variability may be considered a protective mechanism against overuse injuries by altering the characteristics of loading application to minimise accumulation of load in a central region (33). The lack of between-fatigue condition differences displayed by this cohort of the asymptomatic PTA participants during both landing phases of the stop-jump task in the present study suggest that these individuals may not be capable of sufficient movement variability in their landing strategies to accommodate dynamic environment changes, such as when fatigued. We speculate that this limited movement variability may have contributed to these participants developing a PTA and, in turn, predisposes these athletes to patellar tendinopathy. Interestingly, after the conclusion of this study one participant with bilateral PTA contacted the authors to report that they had developed bilateral patellar tendinopathy.

We acknowledge that this study had a small cohort of participants, which may have masked some statistically significant between-fatigue condition differences in the landing technique. Identifying asymptomatic PTA subjects, however, is challenging, given that the subjects have no obvious symptoms. The limited number of stop-jump
trials collected for analysis also prevented full exploration of the notion of low movement variability and its link to patellar tendinopathy. Furthermore, asymptomatic athletes with unilateral and bilateral PTA were treated as one group. The aetiology of unilateral and bilateral patellar tendinopathy is thought to be different (38, 39), suggesting these subgroups may need to be treated separately (39), although this is yet to be confirmed. Future research is therefore recommended to investigate the relationship between low movement variability and patellar tendinopathy. Future research should assess the lower limb landing strategy of a minimum of ten movement trials for each condition, comparing healthy athletes with normal patellar tendons to asymptomatic and symptomatic athletes with unilateral PTA and bilateral PTA as separate sub-groups.

CONCLUSION

Asymptomatic PTA participants did not modify their landing technique or patellar tendon loading during a stop-jump movement in response to muscle fatigue. The lack of between-fatigue condition differences displayed by the asymptomatic PTA participants during both landing phases of the stop-jump task suggest that these individuals may not be capable of sufficient movement variability in their lower limb landing strategies to respond to muscle fatigue. We speculate that this limited movement variability may have contributed to these participants developing a PTA and, in turn, predisposes these athletes to patellar tendinopathy.
REFERENCES


Chapter 8

Summary, Conclusions and Recommendations for Future Research

SUMMARY

In order to provide evidence to develop prevention and rehabilitation programs for patients with patellar tendinopathy, research is required to broaden our understanding of the risk factors associated with patellar tendinopathy, such as patellar tendon loading and fatigue. This thesis aimed to systematically investigate and characterise the patellar tendon loading generated during dynamic landings, and to establish how patellar tendon loading is moderated by fatigue and the presence of a PTA. This was achieved through a series of studies that firstly established a valid and reliable experimental protocol (Part I), before investigating and characterising the patellar tendon loads generated during a dynamic landing task and how this was moderated by fatigue in athletes with normal patellar tendons on diagnostic imaging (Part II) and in asymptomatic athletes with a PTA (Part III).

In Part I (Chapter 2) the experimental protocol to investigate lower limb landing mechanics during a dynamic landing task, a stop-jump movement, was established. It was found that most biomechanical variables quantified to characterise landing technique did not significantly vary as a function of lower limb dominance, implying relative lower limb symmetry throughout the landing phases of the stop-jump task. Nevertheless, asymmetrical patellar tendon loading was noted during the horizontal landing phase in the stop-jump task. Based on this finding it was recommended that a participants’ dominant lower limb should be tested when investigating patellar tendon loading during landing tasks. This will ensure that the experimental design, particularly in terms of lower limb dominance, provides an appropriate framework to investigate
possible mechanics underlying unilateral and bilateral knee joint injuries, such as patellar tendinopathy, during a stop-jump task.

Although there has been extensive research investigating the effects of muscle fatigue on the technique used by athletes to land, the results of these studies are disparate due to between-study differences in experimental design. In order to systematically investigate how patellar tendon loading is moderated by muscle fatigue, a valid and reliable experimental protocol was established in Part I of the thesis (Chapter 3). This lead to the development of a lower limb fatigue protocol that proved to be a reliable and valid method to induce lower limb fatigue as long as the participants performed an entire familiarisation session of the fatigue protocol to a fatigued state, and fully recovered, before any data were collected.

Once the experimental protocol for the thesis was established, Part II (Chapter 4) investigated and characterised patellar tendon loading generated by athletes with normal patellar tendons during the horizontal and vertical landing phases of a stop-jump movement. As hypothesised, the participants generated significantly higher patellar tendon forces but lower vertical ground reaction forces during the horizontal landing phase of the stop-jump task compared to the vertical landing phase. This finding questions the validity of using vertical ground reaction forces to represent patellar tendon forces during the stop-jump movement. The higher patellar tendon loads sustained during the horizontal landing phase are caused by the significantly higher knee joint moment, which is thought to have been created via a greater knee joint moment arm, limited ankle dorsiflexion, greater knee and hip flexion and utilization of the stretch-shortening cycle during the horizontal landing phase compared to the vertical landing phase. We speculate that these between-landing phase differences may have led to the higher patellar tendon loads and greater compression of the posterior aspect of the
proximal patellar tendon during the horizontal landing phase, possibly increasing the likelihood of patellar tendon pathologies in vulnerable athletes.

After characterising patellar tendon loading during dynamic landings, the experimental protocol that was developed in Part I (Chapter 3), was used in Part II (Chapter 5) to investigate the effect of muscle fatigue on landing technique and patellar tendon loads generated during a stop-jump movement by athletes with normal patellar tendons. As hypothesised, muscle fatigue did not alter patellar tendon loading during the vertical landing phase of a stop-jump task in athletes with normal patellar tendons on diagnostic imaging. However, in contrast to the hypothesis, muscle fatigue was found to decrease, not increase, the $F_{PT}$ and LR $F_{PT}$ during the horizontal landing phase of a stop-jump task in athletes with normal patellar tendons. This reduction in patellar tendon loading when fatigued was primarily attributed to the way the participants moderated their landing technique, including significantly reducing their knee joint moment as a consequence of using a smaller knee joint moment arm when landing with less knee flexion and greater hip flexion, and less efficient utilization of the stretch-shortening cycle during the horizontal landing phase. Therefore, athletes with normal patellar tendons were able to decrease their patellar tendon loading when fatigued by altering their landing technique in a way which may have a protective effect on the patellar tendon.

Once the patellar tendon loading generated by athletes with normal patellar tendons during the landing phases of a stop-jump movement had been characterised, Part III (Chapter 6) investigated patellar tendon loading generated by asymptomatic athletes with a PTA during the stop-jump movement. As hypothesised, asymptomatic athletes with a PTA but who had no previous history or clinical signs of patellar tendinopathy, utilised a different lower limb landing technique compared to their
counterparts with normal patellar tendons on diagnostic imaging. It was found during the horizontal landing phase of a stop-jump task asymptomatic athletes with a PTA landed with greater knee flexion and utilised a different hip movement strategy compared to their counterparts with normal patellar tendons. However, in contrast to the hypothesis, asymptomatic athletes with a PTA generated similar patellar tendon loads compared to their counterparts with normal patellar tendons. Based on this finding, it was speculated that it may not be the magnitude of the load that the patellar tendon sustains that is crucial to the development of a PTA but rather the direction of this load and the unique nature of the patellofemoral articulation that are more important. This different landing technique displayed by asymptomatic athletes with a PTA is likely to contribute to increases in the tensile and compressive loads on the proximal part of the patellar tendon, resulting in changes in tendon morphology and, in turn, leading to the development of a PTA and patellar tendinopathy. As the differences in landing displayed by asymptomatic athletes with a PTA primarily occurred in the sagittal plane and were clearly visible during the horizontal landing task, these biomechanical characteristics provide clinicians with important landing assessment criteria against which to identify athletes who have, or are at risk of developing a PTA and, in turn, patellar tendinopathy.

Following characterisation of the patellar tendon loads generated during dynamic landings, the experimental protocol that was developed in Part I (Chapter 3), was used in Part III (Chapter 7) to investigate the effect of muscle fatigue on landing technique and patellar tendon loads generated during a stop-jump movement by asymptomatic athletes with a PTA. In contrast to the hypothesis, these asymptomatic athletes with a PTA did not modify either the magnitude or direction of patellar tendon loading, or their landing technique during a stop-jump movement in response to fatigue.
This finding may suggest that these individuals may be less able to adapt to changes evoked by muscle fatigue and may not be capable of sufficient movement variability in their landing technique to accommodate dynamic environment changes, such as when fatigued. It was speculated that this limited movement variability may have contributed to these participants developing a PTA and, in turn, predisposes these athletes to patellar tendinopathy.

CONCLUSIONS

In characterising the patellar tendon loads generated during the landing phases of a stop-jump task, it was evident that athletes with normal patellar tendons were able to reduce their patellar tendon loads when fatigued. This was achieved by altering their landing technique in a way which may have a protective effect and potentially decrease the likelihood of patellar tendon pathologies in vulnerable athletes. In contrast, asymptomatic athletes with a PTA utilised a different lower limb landing technique than their healthy counterparts with normal patellar tendons, by landing with greater knee flexion and utilising a hip extension rather than a hip flexion strategy. These asymptomatic athletes with a PTA, however, were unable to modify either their patellar tendon load or their landing technique in response to fatigue, and may be less able to adapt to changes evoked by muscle fatigue, therefore placing them at risk of developing patellar tendinopathy due to higher patellar tendon loading.

RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the results of this thesis, the following recommendations are made for future research:

- Lower limb symmetry should not be assumed during a horizontal landing task when investigating the biomechanics of patellar tendinopathy. The
asymmetrical patellar tendon loading noted during the horizontal landing phase suggests that in studies where the magnitude of the patellar force is a primary outcome variable, the participants’ dominant lower limbs should be tested.

- Whether the decrease in patellar tendon loading generated by athletes with normal patellar tendons when fatigued can decrease the risk of developing patellar tendon abnormalities and, in turn, patellar tendinopathy should be investigated.

- A three-dimensional patellar tendon model that can be implemented in future studies to investigate patellar tendon loading generated during dynamic landing tasks should be developed.

- The relationship between low movement variability and patellar tendinopathy warrants investigation.

- A minimum of 10 movement trials for each movement task should be performed when investigating the theory of movement variability in relation to patellar tendinopathy.

- The current thesis was limited to asymptomatic athletes with and without a PTA. It is recommended that research investigating the biomechanics of lower limb landing techniques and associated risk factors for patellar tendinopathy should be expanded to assess discrete sub-groups of athletes including:
  - asymptomatic with a unilateral PTA;
  - asymptomatic with a bilateral PTA;
  - asymptomatic athletes with previous history of unilateral patellar tendinopathy;
Chapter 8: Summary & Conclusions

- asymptomatic athletes with previous history of bilateral patellar tendinopathy;
- symptomatic athletes with unilateral patellar tendinopathy; and
- symptomatic athletes with bilateral patellar tendinopathy.