2010

Are ankle mechanics during drop landings affected by two different measures of passive plantar-flexor flexibility and what are the effects of training: implications for injury?

John William Whitting

University of Wollongong
UNIVERSITY OF WOLLONGONG

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Are ankle mechanics during drop landings affected by two different measures of passive plantar-flexor flexibility and what are the effects of training: Implications for injury?

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

Doctor of Philosophy

from

University of Wollongong

by

John William Whitting

BSc (Hons)

School of Health Sciences

2010
Dedication

This thesis is dedicated to the three most beautiful women in my life; my wife Amanda and my two daughters Caitlin and Jessica. Thank you for allowing me to indulge my curiosity and for putting up with the long days and late nights. You have loved and supported me unconditionally and given me the encouragement and the motivation to make the most of a wonderful opportunity. What a privilege and what a journey!

“The heart of the discerning acquires knowledge; the ears of the wise seek it out.”

Proverbs 18: 15
Declaration

I, John William Whitting, declare that this thesis “Are ankle mechanics during drop landings affected by two different measures of passive plantar-flexor flexibility and what are the effects of training: Implications for injury?”, 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.

John William Whitting
17 December 2010
Publications

The following chapters of this thesis were written as journal articles for publication:


As the primary supervisor, I, Dr Bridget Munro, declare that the greater part of the work in each manuscript listed above is attributable to the candidate, John William Whitting. In each of the above manuscripts, John was primarily responsible for study design and data interpretation, and solely responsible for data collection and data analysis. The initial draft of each manuscript was written by John, who was then responsible for responding to the editorial suggestions of his co-authors. The co-authors assisted in study design, data interpretation and manuscript editing. John has been solely responsible for submitting each manuscript for publication to the relevant journals and has primarily been responsible for responding to reviewer’s comments, with assistance from his co-authors.

John William Whitting
Candidate
17 December 2010

Dr Bridget Munro
Primary Supervisor
17 December 2010
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Thank you, also, to all those who have been members of the Biomechanics Research Laboratory during the years that I have studied here. A special thanks to Karen Mickle, Suzi Edwards, Di Harland, Catherine Wild, Sheridan Gho and Cara Mura for helping me with testing in the lab, helping me to troubleshoot ‘software issues’ or for just helping me to laugh.

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Lastly, I wish to extend a very sincere thanks to the New South Wales Sporting Injury Committee (Australia) for their foresight, belief in the project and financial support.
Abstract

BACKGROUND
Ankle flexibility defined by passive dorsiflexion ROM and plantar-flexor stiffness, is associated with injury risk, particularly during landing tasks involving rapid dorsiflexion and elongation of the plantar-flexor MTU. However, the biomechanical mechanisms associated with poor ankle flexibility that may be inferred as potentially injurious during landing movements are not thoroughly understood. Furthermore, although dorsiflexion ROM and plantar-flexor stiffness may be affected by training, adaptations reported in the literature have been conflicting and the possible effects of training on landing biomechanics have not been investigated.

THESIS AIM
The primary purpose of this thesis was to determine whether variations in ankle dorsiflexion ROM affect ankle biomechanics during a drop landing task and whether these effects were moderated by training that was designed to alter dorsiflexion ROM.

METHODS
Using a randomised controlled trial (RCT) study design, ankle flexibility and landing biomechanics were assessed in 48 male volunteers, each assigned to one of three experimental training interventions (stretch, eccentric strength or landing training) or a control group. Results from this RCT were analysed and presented in three main parts, with each part systematically contributing to the primary thesis aim. Part I explored the baseline RCT data to investigate the relationship between dorsiflexion ROM (in weight-bearing and non-weight-bearing) and plantar-flexor stiffness in order to establish whether these measures of ankle flexibility assessed different characteristics (Chapter 2). Part II again explored the baseline RCT data to determine the effect of dorsiflexion ROM and plantar-flexor stiffness on ankle biomechanics and plantar-flexor loading during drop landings (Chapters 3 and 4). Part III then used the whole RCT data set (baseline and post-intervention) to investigate the effects of different training interventions, designed to increase dorsiflexion ROM or take advantage of the concept of training specificity, on flexibility characteristics and ankle biomechanics during drop landings (Chapters 5 and 6).
Baseline and post-intervention assessments included measurements of passive DROM, passive plantar-flexor stiffness and ankle biomechanics during a single-limb drop landing task. Data collection for the outcome variables characterising landing biomechanics included EMG from four shank muscles and three-dimensional kinematics of the foot and shank as participants landed on a force platform. These biomechanical data provided input for inverse dynamic calculations of ankle kinetics and an estimation of Achilles tendon force generated during landing.

MAJOR CONCLUSIONS

Passive DROM or passive plantar-flexor stiffness do not affect ankle biomechanics during drop landings. However, relative to the demands of the task, athletes with a low DROM may be absorbing landing loads with their plantar-flexor MTU in a more extended length, thereby exposing them to an increased risk of both acute and repetitive overuse plantar-flexor MTU strain injuries. Long-term static stretch training is recommended, as more effective than eccentric strength or task-specific landing training, in order to increase DROM. Static stretch training may also provide some biomechanical advantages during drop landings, with respect to injury mechanisms, by potentially reducing plantar-flexor MTU strain. Specificity provided by landing training may also offer protection from injury during drop landings by developing more synchronous plantar-flexor muscle activation to control the landing movement and increase the time over which to absorb the potentially injurious loads generated during high impact landing tasks.
# Table of Contents

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedication</td>
<td></td>
<td>ii</td>
</tr>
<tr>
<td>Declaration</td>
<td></td>
<td>iii</td>
</tr>
<tr>
<td>Publications</td>
<td></td>
<td>iv</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td></td>
<td>v</td>
</tr>
<tr>
<td>Abstract</td>
<td></td>
<td>vi</td>
</tr>
<tr>
<td>Table of Contents</td>
<td></td>
<td>viii</td>
</tr>
<tr>
<td>List of Tables</td>
<td></td>
<td>xi</td>
</tr>
<tr>
<td>List of Figures</td>
<td></td>
<td>xii</td>
</tr>
</tbody>
</table>

## Chapter 1

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Problem</td>
<td>1</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>STATEMENT OF THE PROBLEM</td>
<td>7</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>10</td>
</tr>
</tbody>
</table>

## PART I

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are two different methods of assessing passive plantar-flexor flexibility correlated?</td>
<td>16</td>
</tr>
</tbody>
</table>

## Chapter 2

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passive plantar-flexor stiffness is poorly correlated with passive dorsiflexion range of motion</td>
<td>17</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>17</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>18</td>
</tr>
<tr>
<td>METHODS</td>
<td>20</td>
</tr>
<tr>
<td>Participants</td>
<td>20</td>
</tr>
<tr>
<td>Joint ROM and plantar-flexor stiffness measures</td>
<td>20</td>
</tr>
<tr>
<td>Statistical analyses</td>
<td>23</td>
</tr>
<tr>
<td>RESULTS</td>
<td>23</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>25</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>28</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>29</td>
</tr>
</tbody>
</table>

## PART II

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are ankle mechanics during drop landings affected by two different measures of plantar-flexor flexibility?</td>
<td>33</td>
</tr>
</tbody>
</table>

## Chapter 3

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dorsiflexion capacity affects Achilles tendon loading during drop landings</td>
<td>34</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>34</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>35</td>
</tr>
<tr>
<td>METHODS</td>
<td>37</td>
</tr>
<tr>
<td>Participants and DROM measure</td>
<td>37</td>
</tr>
<tr>
<td>Drop landing protocol</td>
<td>39</td>
</tr>
<tr>
<td>Muscle activity</td>
<td>39</td>
</tr>
<tr>
<td>Ground reaction forces</td>
<td>41</td>
</tr>
<tr>
<td>Kinematics and joint kinetics</td>
<td>41</td>
</tr>
<tr>
<td>Statistical analyses</td>
<td>43</td>
</tr>
</tbody>
</table>
RESULTS .......................................................... 43
  Electromyography .............................................. 43
  Kinetics and kinematics ...................................... 44
  DROM percentages ............................................ 46
DISCUSSION .......................................................... 47
CONCLUSIONS ......................................................... 52
REFERENCES .......................................................... 53

Chapter 4
  Effects of passive plantar-flexor stiffness on ankle mechanics during drop landings ..................... 57
  ABSTRACT .......................................................... 57
  INTRODUCTION ..................................................... 58
  METHODS ............................................................ 61
    Participants ....................................................... 61
    Passive plantar-flexor stiffness ............................ 61
    Drop landing protocol ........................................ 63
      Ground reaction forces .................................... 63
      Kinematics and joint kinetics ............................. 64
    Statistical analyses .......................................... 65
  RESULTS .......................................................... 65
  DISCUSSION ......................................................... 66
  CONCLUSIONS ....................................................... 69
  REFERENCES .......................................................... 70

PART III
  How does training affect measures of plantar-flexor flexibility and will training moderate ankle mechanics during drop landings? ............................................. 74

Chapter 5
  Effects of three different training methods on plantar-flexor strength and flexibility: A randomised controlled trial ..................................................... 75
  ABSTRACT .......................................................... 75
  INTRODUCTION ..................................................... 76
  METHODS ............................................................ 78
    Participants and study design ............................... 78
    Training interventions ........................................ 81
    Assessments of dorsiflexion ROM, plantar-flexor stiffness and eccentric strength ..................... 84
    Statistical analyses .......................................... 85
  RESULTS .......................................................... 86
  DISCUSSION ......................................................... 86
  CONCLUSIONS ....................................................... 90
  REFERENCES .......................................................... 90
Chapter 6  Effects of plantar-flexor strength and flexibility training on ankle mechanics during drop landings: A randomised controlled trial……………………………. 94
ABSTRACT ………………………………………….. 94
INTRODUCTION ……………………………………. 95
METHODS ………………………………………….. 97
  Participants and study design ......................... 97
  Training interventions ............................... 99
  Drop landing technique assessment............... 101
  Statistical analyses ................................. 103
RESULTS .................................................. 104
  Muscle activity........................................ 104
  Ground reaction forces and ankle joint kinematics
    and kinetics........................................ 104
DISCUSSION ............................................ 108
CONCLUSIONS .......................................... 110
REFERENCES ............................................ 111

Chapter 7  Summary, conclusions and recommendations for future research………………………………………… 116
SUMMARY ............................................... 116
CONCLUSIONS .......................................... 120
RECOMMENDATIONS FOR FUTURE RESEARCH 121
### List of Tables

| Table 1 | Mean (± SD) values for ground reaction force, kinematic and kinetic data, representing the effects of DROM group and the effects of vertical descent velocity during the slow (2.25 m.s⁻¹) and fast (3.21 m.s⁻¹) drop landings. | 45 |
| Table 2 | Mean (± SD) values for all descriptive variables characterising participants in the low (LPS) and high (HPS) passive plantar-flexor stiffness groups. | 63 |
| Table 3 | Mean (± SD) values for the ground reaction force, kinematic and kinetic data, representing the effects of passive plantar-flexor stiffness group and vertical descent velocity during the slow and fast drop landings. | 66 |
| Table 4 | Mean (± SD) data and compliance rates for participants in the experimental training and control groups. | 80 |
| Table 5 | Mean (± SD) values for the calf muscle flexibility and strength measures. Data represent the values for baseline and post-intervention and the mean changes resulting from the training intervention for each group. | 87 |
| Table 6 | Mean (± SD) values for temporal variables characterising the timing of muscle activation events relative to initial foot-ground contact. | 105 |
| Table 7 | Mean (± SD) values for variables characterising ground reaction forces and ankle joint kinematics and kinetics during drop landings, for each training group. | 107 |
List of Figures

Figure 1  Schematic representation of thesis design and study papers.............. 9
Figure 2  Standardised position for measuring weight-bearing dorsiflexion ROM (DROM)................................................................. 21
Figure 3  Schematic illustration of the method for calculating passive stiffness from the torque-angle data generated by the KinCom dynamometer................................................................. 22
Figure 4  Pearson’s correlation demonstrating the association between non-weight-bearing (NWB) and weight-bearing (WB) measures of ankle dorsiflexion range of motion (DROM).................. 24
Figure 5  Pearson’s correlation demonstrating the association between measures of passive plantar-flexor stiffness and weight-bearing (WB) ankle dorsiflexion range of motion (DROM)........... 24
Figure 6  Pearson’s correlation demonstrating the association between measures of passive plantar-flexor stiffness and non-weight-bearing (NWB) ankle dorsiflexion range of motion (DROM).... 25
Figure 7  Anatomical sites used to define the foot and shank segments in Visual3D software................................................................. 42
Figure 8  Mean (± SD) data pooled across DROM groups, representing the effects of vertical descent velocity on muscle burst onsets and offsets during the slow (2.25 m.s⁻¹) and fast (3.21 m.s⁻¹) drop landings........................................................................................................ 44
Figure 9  Mean (+ SD) ankle dorsiflexion angles as a percentage of DROM at critical events........................................................................... 46
Figure 10 Typical Achilles tendon force (ATF) and ground reaction force (GRF) traces depicting the mean values for a single participant during fast (3.21 m.s⁻¹) vertical descent velocity drop landing trials......................................................................................................................... 51
Figure 11 Schematic diagram demonstrating overall experimental design, investigator and participant blinding and the flow of participants from enrolment through to follow-up assessment and analysis........................................................................................................................................ 79
Figure 12 Demonstration of the four static stretch poses used during training........................................................................................................ 81
Figure 13 An example of a participant performing landing training from the maximum single limb landing height (72 cm) in Week 6 of the training intervention........................................................... 83
Figure 14 Significant group x day interaction ($p = 0.014$) for mean data pertaining to the peak EMG amplitude for lateral gastrocnemius during drop landings......................................................................................................................... 104
Figure 15 Significant group x day interaction ($p = 0.040$) for mean data pertaining to the time to reach the peak dorsiflexion angle during drop landings...................................................................................... 106
Figure 16 Significant group x day interaction ($p = 0.032$) for mean data pertaining to the ankle plantar-flexion angle at initial foot-ground contact during drop landings.............................................................. 106
Chapter 1

The Problem

INTRODUCTION

The plantar-flexor muscle-tendon unit (MTU), primarily comprised of the gastrocnemius and soleus muscles and the Achilles tendon, is an integral part of ankle and lower limb function. When these plantar-flexor muscles contract concentrically in unison they plantar-flex and invert the foot and ankle and provide up to 93% of any plantar-flexion moment. Conversely, dorsiflexion and eversion of the foot and ankle lengthen the plantar-flexor MTU. Although ankle dorsiflexion range of motion (ROM) is restricted by bony limitations or other characteristics of the muscles and tendons surrounding the ankle joint, dorsiflexion and eversion ROM are largely determined by the plantar-flexor MTU. Furthermore, the amount of force or tension that a muscle can generate or absorb throughout its ROM is affected by the length of the MTU. As such, dorsiflexion ROM is frequently used as a measure of disease, function, performance and injury risk.

The amount of available dorsiflexion ROM contributes to the ability of an individual to perform a multitude of dynamic weight-bearing tasks, including level-ground gait, stair descents and dynamic impact tasks such as landing movements. Landing tasks performed in sporting activities place very high demand on structures of the ankle joint because the dorsiflexion ROM used during each landing contributes substantially to the dissipation of the high ground reaction forces encountered upon ground contact. Landing movements typically involve higher impact velocities compared to gait tasks, ranging from 2.0 m.s\(^{-1}\) to over 6.0 m.s\(^{-1}\). These high impact velocities in turn result in average peak ground reaction forces of between 2.6 and 18 times body weight (BW). During landing tasks the lower limb is the primary
tool for absorbing the impact generated upon ground contact, with the ankle being the first major joint to be loaded via the calf muscles\textsuperscript{15-17}.

The high impact forces during landings mean that athletes who participate in sports which involve frequent landings, such as gymnastics, Australian Rules football, soccer, basketball and volleyball, are regularly exposed to a high risk of ankle and lower limb injury\textsuperscript{22-28}. Due to these high loads imposed upon the various structures of the ankle joint during such dynamic sports, ankle injuries account for up to 25-30\% of all sporting injuries\textsuperscript{27}. In basketball, for instance, ankle injuries occur at a rate of 3.85 per 1000 participants, with the most common mechanism for injury being the landing movement\textsuperscript{24}. Similarly, in volleyball and gymnastics, the ankle is the most commonly injured body part, with research demonstrating that 41\% of all volleyball injuries\textsuperscript{28} and 46\% of all gymnastics injuries occur at the ankle\textsuperscript{25}, with the landing phase of floor exercises identified to be the greatest source of risk\textsuperscript{25}.

In addition to common ankle joint injuries such as sprains and fractures, muscle-tendon strain injuries account for as many as 50\% of all sporting injuries\textsuperscript{29}. Not only are musculotendinous injuries commonplace in sport, but Achilles tendinopathies and gastrocnemius muscle strains are among the most prevalent\textsuperscript{22, 29-31}. Force dissipation through rapid eccentric lengthening of the plantar-flexor MTU, as a braking mechanism to decelerate the body when landing\textsuperscript{32}, exposes both the Achilles tendon and the plantar-flexor muscle fibres to substantial injury risk\textsuperscript{30, 31, 33}. This is particularly the case in sports involving explosive stretch shortening cycle or eccentric movements such as jumping and landing\textsuperscript{22, 33-35}.

Researchers have suggested a link between decreased dorsiflexion ROM and a variety of injuries such as ankle sprains and fractures and Achilles tendon overuse injuries\textsuperscript{10, 29, 36}. A limited amount of biomechanical research has shown that dorsiflexion
ROM may affect the performance of different dynamic tasks, with low dorsiflexion ROM negatively associated with balance and gait tasks in the elderly\(^5\) and stair descents in young males\(^{14}\). As such, having reduced dorsiflexion ROM may place individuals at a biomechanical disadvantage in terms of both function and loading during weight-bearing tasks.

Although a landing movement is a multi-joint task\(^{37}\), primarily controlled by the lower limb, the ankle is the first major joint beyond the foot to absorb the ground reaction force\(^{15,16}\). Nonetheless, it must be acknowledged that flexion in joints such as the knee can also substantially influence overall lower limb stiffness and load absorption during landings\(^{21,38}\). Although individuals have been shown to use greater knee flexion to mitigate ground reaction forces in response to greater landing heights, this effect was not demonstrated during single limb landings\(^{38}\). Interestingly, research has also shown that individuals chose to use greater ankle ROM during a double-limb landing task in response to increases in landing velocity, possibly to mitigate increases in ground reaction force by plantar-flexing more at initial foot-ground contact\(^{18,20}\). Furthermore, ankle dorsiflexion during load absorption controlled by eccentric contraction of the plantar-flexor muscles, has been shown to moderate the overall multi-joint landing strategy and the loads subsequently imposed upon the more proximal joints of the lower limb\(^{15,16,37}\). Lower limb joint ROM during landing influences the amount of time taken to absorb the impact, thereby affecting ground reaction force and joint loading\(^{39,40}\). It is reasonable to conclude that a reduced passive dorsiflexion ROM may affect the dynamic landing dorsiflexion ROM, which in turn may decrease control of the dorsiflexion movement or increase plantar-flexor MTU strain if these structures are over-lengthened. This may account for some of the findings of retrospective research that demonstrates an association between decreased passive dorsiflexion ROM
and sport-related injuries such as ankle sprains, Achilles tendon overuse injuries and plantar-flexor muscle strain injuries, particularly during landing sports\textsuperscript{10,22,29}.

Another gauge of joint flexibility associated with acute and overuse strain injuries is MTU compliance, often defined or characterised by measures of whole MTU or tendon stiffness, or resistance to stretch\textsuperscript{12,41}. Furthermore, plantar-flexor MTU compliance has been used by researchers to assess dorsiflexion ROM\textsuperscript{14} and has been proposed as a determinant of dorsiflexion ROM\textsuperscript{11,42}. Nonetheless, there is division within the literature regarding possible associations between MTU compliance and injury risk. Researchers have suggested that more compliant and energy-absorbent tendons are less likely to transfer excessive strain energy to adjacent muscle fibres during lengthening actions such as those found in stretch shortening cycle activities, thereby providing some protection from muscle strain injuries\textsuperscript{33}. More compliant tendons are linked to improvements in stretch shortening cycle performance\textsuperscript{43} and may also be able to absorb more strain energy themselves before becoming injured\textsuperscript{33}. This speculation regarding tendon compliance has strong implications for overall plantar-flexor MTU compliance and MTU strain injury risk because the Achilles tendon is the largest tendon in the human body\textsuperscript{35,44}, substantially larger than other tendons crossing the ankle joint and, not surprisingly, has been strongly correlated with plantar-flexor stiffness\textsuperscript{45}.

Contrastingly, other research has indicated an association between a reduced capacity for MTU structures to resist stretch and a higher propensity for early structural failure\textsuperscript{46}, which supports the widely accepted notion that MTU injury risk may be more a function of the magnitude of strain and not necessarily the magnitude of the applied force\textsuperscript{34,47}. Highly compliant MTU structures may stretch further under a given tensile load, suffering strain overload as they stretch toward the end of their normal range\textsuperscript{29,44}. 

4
As such, there is a duality in the evidence, with suggestions that both low and high plantar-flexor stiffness may be implicated in increased injury risk during lengthening dorsiflexion movements, such as those experienced during landing activities.

Although a limited dorsiflexion ROM appears to be strongly associated with injury risk during dynamic tasks, there is considerable variability in dorsiflexion ROM assessment techniques\textsuperscript{14, 48-50}, which makes comparisons between studies difficult. For example, the magnitude of dorsiflexion ROM measured in weight-bearing differs to that in non-weight-bearing\textsuperscript{48}, and both measures differ depending on the amount of knee joint flexion\textsuperscript{51}. Furthermore, although some research has associated passive plantar-flexor stiffness with dorsiflexion ROM, because these studies assessed both measures in non-weight-bearing positions\textsuperscript{11, 12}, the results may not be relevant when assessing the ability to perform weight-bearing, closed kinetic chain tasks\textsuperscript{49, 52}. Therefore, associations between functional weight-bearing measures of dorsiflexion ROM and plantar-flexor stiffness, as well as associations between these measures and dynamic biomechanics during tasks such as landings are poorly understood.

Nonetheless, due to the association between low joint ROM and injury risk and ambiguity in the literature regarding the effects of MTU stiffness on injury risk, much research has been conducted to investigate the effectiveness of different training programs designed to increase ROM\textsuperscript{11, 42, 53}. Most interventions aimed at increasing joint ROM involve stretch training protocols including static, dynamic, ballistic and proprioceptive neuromuscular facilitation (PNF) stretching\textsuperscript{3, 11, 42, 43, 53-55}, although other training methods include eccentric strength and task-specific training\textsuperscript{56-58}. Static stretching is the most common of the stretch training programs as it is easy to perform, effective and relatively safe\textsuperscript{3, 55}. It should be noted, however, that the effects of static stretch training on MTU compliance are not well understood. Although there is some
evidence to suggest that static stretching may increase MTU compliance\(^1\), \(^2\), \(^5\), other research has demonstrated MTU compliance may not be affected by static stretch training\(^4\), \(^5\). Eccentric strength training has been shown to increase joint ROM\(^5\), \(^8\) and increase MTU compliance\(^5\), although most research regarding MTU length changes has been limited to computer modelling or animal studies\(^6\), \(^7\). As human adaptations to eccentric exercise are assessed non-invasively\(^6\), mechanisms for MTU length and compliance changes are not well understood.

There is a dearth of task-specific training studies investigating the effects of training on joint ROM and MTU compliance, particularly with respect to the ankle and plantar-flexor MTU. Only two published studies were found that assessed MTU stiffness adaptations, one involved running that measured both dorsiflexion ROM and MTU stiffness adaptations, and one involving hopping and drop jumping movements. When participants were involved in running training in isolation, passive MTU stiffness significantly decreased without changing dorsiflexion ROM, yet a combination of running and static stretch training produced a larger increase in dorsiflexion ROM (with no change to passive MTU stiffness) compared to an isolated stretch training program\(^5\). Hopping and drop jump training produced a significant increase in active ankle joint stiffness without affecting Achilles tendon stiffness\(^6\). Therefore, depending on the task trained, MTU adaptations appear to be variable, although the active stimulus in both of these training studies involved movements that contained both eccentric and concentric muscle actions\(^5\), \(^6\). Landing movements in contrast, involve only an eccentric phase, as the plantar-flexor MTU is eccentrically elongated during rapid dorsiflexion. As such, it is reasonable to speculate that task-specific landing training may provide the necessary ballistic stretch and eccentric strength stimuli to affect dorsiflexion ROM and plantar-flexor stiffness, possibly negating the need for athletes to perform additional modes of
exercise to train these parameters. Nonetheless, due to the association between decreased dorsiflexion ROM and increased injury risk, particularly in landing sports, and the varying effects of training on ROM, it is critical to understand which training programs may induce plantar-flexor MTU changes capable of providing protection from strain type injuries, as well as understanding how these changes might affect ankle mechanics during landing movements.

**STATEMENT OF THE PROBLEM**

Ankle flexibility defined by passive dorsiflexion ROM and plantar-flexor stiffness, is associated with injury risk, particularly during landing tasks involving rapid dorsiflexion and elongation of the plantar-flexor MTU. However, the biomechanical mechanisms associated with poor ankle flexibility that may be inferred as potentially injurious during landing movements are poorly understood. Furthermore, although dorsiflexion ROM and plantar-flexor stiffness may be affected by training, adaptations reported in the literature have been conflicting and the possible effects of training on landing biomechanics are not understood. Therefore, the primary purpose of this thesis was to determine whether variations in ankle dorsiflexion ROM affect ankle biomechanics during a simple drop landing task, designed to strain the plantar-flexor MTU and whether these effects were moderated by training that was designed to alter dorsiflexion ROM.

In order to achieve this overall thesis aim, a randomised controlled trial (RCT) study was conducted in which ankle flexibility and landing biomechanics were assessed before and after a cohort of healthy male volunteers performed one of three experimental training interventions (stretch, eccentric strength or landing training) or participated as controls. Results from this RCT were analysed and presented in three
main parts, with each part systematically contributing to the overall thesis aim (Fig. 1). Due to disparities in the literature regarding joint flexibility measurement techniques and their relationships to each other, Part I explored the baseline RCT data to investigate the relationship between dorsiflexion ROM (in weight-bearing and non-weight-bearing) and plantar-flexor stiffness in order to establish whether these measures of ankle flexibility assessed different characteristics (Chapter 2). As passive dorsiflexion ROM and plantar-flexor stiffness may be related to different aspects of ankle flexibility, with different implications for landing biomechanics and subsequent injury risk, Part II again explored the baseline RCT data to determine the effects of dorsiflexion ROM and plantar-flexor stiffness on ankle biomechanics and plantar-flexor loading during drop landings (Chapters 3 and 4). Part III then used the whole RCT data set (baseline and post-intervention) to investigate the effects of different training interventions, designed to increase dorsiflexion ROM or take advantage of the concept of training specificity, on flexibility characteristics and ankle biomechanics during drop landings (Chapters 5 and 6). A summary of the findings from this thesis, together with the thesis conclusions and recommendations, can be found in Chapter 7.
Chapter 1

**Thesis purpose**
To determine whether variations in ankle dorsiflexion ROM affect ankle biomechanics during a drop landing task and whether these effects were moderated by training that was designed to alter dorsiflexion ROM

**Part I**
Are different methods of assessing passive plantar-flexor flexibility correlated?

**Chapter 2**
Passive plantar-flexor stiffness is poorly correlated with passive dorsiflexion range of motion

**Part II**
Are ankle mechanics during drop landings affected by two different measures of plantar-flexor flexibility?

**Chapter 3**
Dorsiflexion capacity affects Achilles tendon loading during drop landings

**Chapter 4**
Effects of passive plantar-flexor stiffness on ankle mechanics during drop landings

**Part III**
How does training affect measures of plantar-flexor flexibility and will training moderate ankle mechanics during drop landings?

**Chapter 5**
Effects of three different training methods on plantar-flexor flexibility and strength: A randomised controlled trial

**Chapter 6**
Effects of plantar-flexor flexibility and strength training on ankle mechanics during drop landings: A randomised controlled trial

**Thesis Recommendations**
Screening and training strategies to minimise the risk of ankle and plantar-flexor muscle-tendon injuries in landing sport

**Figure 1:** Schematic representation of thesis design and study papers.
REFERENCES


PART I

Are different methods of assessing passive plantar-flexor flexibility correlated?
Chapter 2

Passive plantar-flexor stiffness is poorly correlated with passive dorsiflexion range of motion

This chapter is an amended version of the manuscript: Whitting JW, Steele JR, McGhee DE and Munro BJ. Passive plantar-flexor stiffness is poorly correlated with passive dorsiflexion range of motion. *British Journal of Sports Medicine*. Submitted for publication December, 2010.

ABSTRACT

Weight-bearing (WB) and non-weight-bearing (NWB) measures of passive dorsiflexion range of motion (DROM), together with plantar-flexor stiffness, are different measures of ankle flexibility and may each be implicated in injury risk during dynamic tasks such as landings. The purpose of this study was to determine whether passive measures of standing WB DROM, prone NWB DROM and plantar-flexor stiffness were correlated, thereby assessing similar mechanical characteristics. Passive WB DROM, NWB DROM and plantar-flexor stiffness were quantified for 42 males (22.8 ± 5.0 years), with the relationship between each data set calculated using Pearsons’ correlations. Passive WB DROM (mean = 43.0 ± 5.0°) was significantly greater than NWB DROM (29.8 ± 5.9°; \(p < 0.001\)). The WB DROM and NWB DROM data sets were poorly correlated (\(r^2 = 0.18\)) and WB DROM and NWB DROM were each poorly correlated with passive plantar-flexor stiffness (1.48 ± 0.55 Nm.°\(^{-1}\); \(r^2 = 0.04\) and \(r^2 = 0.14\), respectively). Passive plantar-flexor stiffness was not well associated with either assessment for DROM, indicating that passive plantar-flexor stiffness may not be a strong determinant of DROM. Furthermore, as WB and NWB assessments of DROM were not strongly associated, the functional capacity of the talocrural joint to cope with
dorsiflexion during weight-bearing tasks may actually be underestimated or even misrepresented by non-weight-bearing measures of DROM. Therefore, although ankle DROM and plantar-flexor muscle-tendon unit stiffness may be implicated in injury risk during weight-bearing tasks such as landings, it is likely due to different biomechanical mechanisms.

**INTRODUCTION**

Various measures of joint flexibility, such as range of motion (ROM), have been studied extensively in investigations of injury incidence, risk and prevention. Despite this extensive research ambiguity exists regarding what constitutes joint ROM and how it can best be measured\(^1\text{-}\text{6}.\) Reduced ankle dorsiflexion ROM (DROM) has been associated with increased injury risk in both acute and overuse injuries to the ankle joint and surrounding tissues, which are among the most common of all sporting injuries\(^7\text{-}\text{11}.\)

One proposed determinant of joint ROM\(^5\text{, }12\), and in turn injury risk\(^13\), is muscle-tendon unit (MTU) compliance. Compliance of a MTU is often defined and measured as passive stiffness or as tolerable passive torque\(^1\text{, }14\). Long-term stretching training studies have demonstrated reductions in passive MTU tension\(^15\) or passive MTU stiffness\(^5\) with concomitant increases in joint ROM, suggesting that joint ROM may be dependent upon MTU stiffness. Other research, however, has shown significant increases in joint ROM post-stretch training, with no change in MTU stiffness\(^12\text{, }16\text{, }17\). Although limited ROM at joints, such as the ankle, has been linked to dysfunctional movement and increased risk of injury\(^3\text{, }7\text{, }18\), the biomechanical determinants and restraints to ROM are not thoroughly understood. Therefore, the relationship between various measures of joint flexibility, such as joint ROM and MTU compliance, as well
as whether a stiff MTU is responsible for restricting joint ROM and whether this affects
injury risk, remains unknown.

In terms of the ankle, DROM is commonly assessed as a gauge of health and
function in elderly, pathological or highly active populations\textsuperscript{7, 18, 19}, and both researchers
and clinicians agree that sufficient DROM is required to perform athletic tasks and
activities of daily living effectively and safely\textsuperscript{2, 20}. Assessment techniques used to
measure DROM, however, vary considerably in the literature\textsuperscript{3, 21-23}. Ankle DROM will
vary if it is measured in weight-bearing versus non-weight bearing positions\textsuperscript{21} and will
also vary between knee-flexed and knee-extended postures\textsuperscript{24}. This variability in DROM
assessment methodology makes comparison between studies, and any subsequent
determination regarding sufficiency of DROM for different tasks, difficult. As tasks
such as walking, running, jumping and landing are performed in a closed kinetic chain,
it seems logical to measure DROM in a weight-bearing position, approximating
functional requirements\textsuperscript{21, 22}, rather than in a non-weight-bearing position. Although
reliable methods for assessing functional DROM in weight-bearing positions have been
developed\textsuperscript{22, 25, 26}, there has been limited research regarding the correlation between
weight-bearing and non-weight-bearing methods of assessing DROM\textsuperscript{21}. The lack of
conclusive evidence is problematic for clinicians and trainers, particularly when non-
weight-bearing assessments of DROM are used to determine whether a patient or athlete
has sufficient ankle ROM to perform a weight-bearing task\textsuperscript{27}. Furthermore, although
limited research has associated passive MTU stiffness with joint ROM\textsuperscript{1, 5}, these studies
have used non-weight-bearing open kinetic chain positions. It remains unknown
whether these associations hold for closed kinetic chain weight-bearing DROM
assessments. Therefore, the purpose of this study was to investigate the relationship
between non-weight-bearing DROM, weight-bearing DROM and passive MTU
stiffness. We hypothesised that non-weight-bearing measures of ankle DROM and passive stiffness would be significantly and strongly correlated, although poorly correlated with weight-bearing DROM.

METHODS

Participants

Forty eight physically active males were recruited from within the campus population of the University of Wollongong to participate in the study. Prior to participating, each recruit completed injury history and ‘Physical Activity Readiness’ questionnaires and written informed consent. Potential participants with any current or previous injuries contraindicated for completing the experimental protocol were excluded. Ethical clearance for the study was obtained from the University of Wollongong Human Research Ethics Committee (HE06/333).

Joint ROM and plantar-flexor stiffness measures

The test limb selected for all assessments was determined by asking each participant to drop from a height of 32 cm on to their preferred landing foot. The weight-bearing (WB) DROM (Fig. 2) for each participant’s test limb was measured with a Gollehon extendable goniometer (Model 01135; Lafayette Instrument Co., USA) using the standing lunge test developed by Bennell et al. A high reliability coefficient (ICC=0.97, two-way mixed effects model for consistency of single measures) for the same assessor [JWW], irrespective of the leg measured, was established using this method by measuring four trials for each leg on six pilot subjects unassociated with the study over three separate days. Passive non-weight-bearing (NWB) DROM was measured with each participant in a prone position on a KinCom dynamometer (Kinetic Communicator, Chattecex Corp., Chattanooga, TN) with their test foot firmly strapped to
the dynamometer foot-plate. Dense rubber padding was placed beneath the ankle strap and between the malleoli and the ankle housing on the foot pedal, thereby preventing lateral ankle movement or ‘heel lift’ during dorsiflexion movements. The lateral malleolus was aligned with the axis of rotation of the dynamometer head and, using the lateral femoral condyle and the greater trochanter, the knee was positioned in a statically flexed position (10°; goniometer). The NWB DROM was deemed the maximum angle of three trials of passive ankle dorsiflexion, whereby an examiner manually rotated the foot pedal from 5° of plantar-flexion to each participant’s self-selected stretch limit of dorsiflexion\textsuperscript{21}, without inducing abnormal pain.

![Diagram](image)

**Figure 2:** Standardised position for measuring weight-bearing dorsiflexion ROM (DROM). A = lateral femoral condyle; B = lateral malleolus; C = centre of heel; D = centre of hallux; \( \theta \) = ankle flexion angle measured during the DROM protocol.

Passive plantar-flexor stiffness was measured in the same position used for NWB DROM assessment on the KinCom dynamometer, with the ankle passively dorsiflexed at a slow, constant velocity of 5°.s\textsuperscript{-1} from 5° of plantar-flexion to their pre-determined stretch limit, ensuring that the participants relaxed their ‘calf’ muscles and did not actively resist the movement. A slow velocity was used to limit muscular activation...
from stretch reflexes\textsuperscript{1,12,14,28}. Passive plantar-flexor stiffness values were determined by measuring the slope of the torque-angle curve\textsuperscript{1,28} generated between 15° and 20° of dorsiflexion (Fig. 3). Analog data pertaining to the angular position, angular velocity and torque were sampled at 100 Hz directly from the KinCom PC via a National Instruments DAQpad 6015/1016 using MyoResearch XP collection software (Version 1.04.02, Noraxon Inc, Scottsdale, AZ).

Electromyography data were simultaneously sampled from the tibialis anterior, soleus and medial and lateral gastrocnemius muscles and synchronised with the KinCom output data using the same MyoResearch software to ensure that the movements were truly passive. The surface electrode sites were located according to the recommendations of Cram et al.\textsuperscript{29} and were confirmed by manually palpating the centre of each muscle belly. Silver/silver chloride surface electrodes (Ambu Blue Sensor N-00-S; Medicotest, Ølstykke, DEN) were aligned parallel with the direction of the muscle fibres and with an inter-electrode spacing no greater than 22 mm to minimise cross-talk between adjacent muscle bellies. A reference electrode was positioned over the tibial tuberosity. The EMG signals were relayed from the electrodes to a Telemyo 900 battery-powered transmitter (Noraxon, Scottsdale, AZ), and then transmitted to a

\textbf{Figure 3:} Schematic illustration of the method for calculating passive stiffness from the torque-angle data generated by the KinCom dynamometer.
Telemyo 900 receiver via an antenna and sampled at 1000 Hz (bandwidth 16-500 Hz). Replicating previous studies, a research assistant, trained by the primary researcher in the present experiment, monitored the EMG traces in real-time during data collection to ensure there was no myoelectric activity and gave feedback to the participants where necessary\textsuperscript{30-32}. During later analysis of all EMG signals, any trials that involved visible muscle activation were discarded, resulting in data sets for a cohort of 42 participants for the subsequent statistical analyses (mean age = 22.8 ± 5.0 years; height = 180.3 ± 7.8 cm; mass = 75.7 ± 10.9 kg).

**Statistical analyses**

All data sets were tested for normality using the Kolmogorov-Smirnov statistic with a Lilliefors significance correction. Mean (± SD) values were calculated for the WB DROM, NWB DROM and passive stiffness data sets and a paired samples $t$-test was performed to compare WB DROM and NWB DROM. A series of Pearson’s correlations were then performed, comparing the data sets for each of the outcome variables. An alpha level was set at 0.05 for all statistical analyses and all data were analysed using SPSS for Windows (SPSS Inc., Chicago, IL; Version 17).

**RESULTS**

Mean (± SD) values for WB DROM, NWB DROM and passive stiffness were 43.0 ± 5.0°, 29.8 ± 5.9° and 1.48 ± 0.55 Nm.°$^{-1}$, respectively. WB DROM was significantly ($p < 0.001$) greater than NWB DROM. The WB DROM and NWB DROM data sets were poorly correlated (Fig. 4) with only 18% of the NWB DROM values explained by their relationship with the WB DROM values. Measures for WB DROM and NWB DROM were also each poorly correlated with the measure of passive plantar-flexor stiffness (Figs. 5 and 6) with only 4% and 14% of the values for passive plantar-
flexor stiffness explained by the corresponding measures of WB DROM and NWB DROM, respectively.

**Figure 4:** Pearson’s correlation demonstrating the association between non-weight-bearing (NWB) and weight-bearing (WB) measures of ankle dorsiflexion range of motion (DROM).

**Figure 5:** Pearson’s correlation demonstrating the association between measures of passive plantar-flexor stiffness and weight-bearing (WB) ankle dorsiflexion range of motion (DROM).
DISCUSSION

The mean WB DROM and NWB DROM values reported in the current study are similar to values reported by others, using similar cohorts and DROM assessment techniques\textsuperscript{1, 5, 22, 26, 33}. The mean plantar-flexor stiffness value (1.48 ± 0.55 Nm.°\textsuperscript{-1}; N = 42) also closely approximated the mean passive plantar-flexor stiffness reported by Kubo et al. (~1.4 Nm.°\textsuperscript{-1})\textsuperscript{1}, using a similar cohort of young adult males. In agreement with the literature, our cohort was able to achieve significantly greater DROM when standing compared to the prone NWB DROM position\textsuperscript{21}. Furthermore, although WB DROM and NWB DROM were positively and significantly correlated (Fig. 4; \(p = 0.004\)), the strength of the correlation was weak (\(r^2 = 0.18\)). Therefore, our results show that non-weight-bearing assessments of DROM may not reflect the capacity of the talocrural joint to flex in more functional weight-bearing positions.

Gait tasks, activities of daily living and sporting activities usually require individuals to dorsiflex their ankles in weight-bearing postures. Healthy individuals may
use between 10° and 20° of DROM in a weight-bearing position during unimpeded level-ground gait\textsuperscript{34} and between 20° and 40° of WB DROM when performing more demanding tasks such as descending stairs or landing from a jump\textsuperscript{3, 26}. When assessing an individual’s ability to achieve the required dorsiflexion angle to perform any given weight-bearing task safely and effectively, a non-weight-bearing assessment may underestimate\textsuperscript{21} and even misrepresent their true and functional ankle dorsiflexion capacity\textsuperscript{18, 22, 25}. Although patients may be contraindicated to perform a WB DROM assessment during rehabilitation from an ankle injury, clinicians must be aware that a lack of correlation between weight-bearing and non-weight-bearing assessments of DROM, suggests that they should not be used interchangeably. As many gait and sporting tasks are performed during weight-bearing closed kinetic chain activities, it is recommended that the available passive DROM required should be assessed in a similar weight-bearing manner.

The results of the present study also demonstrate that plantar-flexor MTU compliance, as represented by the passive plantar-flexor stiffness measures, was only weakly associated with either measure of DROM (Figs. 5 and 6). Consequently, although passive MTU stiffness assessments are often made using non-weight-bearing methods\textsuperscript{1, 5}, there may be no justification for assessing DROM in the same non-weight-bearing position in order to relate the two measures. If high or low plantar-flexor stiffness is implicated in injury potential during dynamic ankle dorsiflexion movements that elongate the plantar-flexors, it may be for reasons other than the effects of MTU stiffness on joint ROM. Therefore, although a limited passive DROM may alter ankle kinematics or potentially increase plantar-flexor MTU strain during weight-bearing loading tasks\textsuperscript{3, 18, 26}, high or low plantar-flexor stiffness may affect injury potential by alternative mechanisms. For instance, the stiffness of one or more individual structures
within the MTU, including muscle, fascia and tendon, may influence overall MTU stiffness and, therefore, be involved in function and injury risk by influencing the stiffness of adjacent structures.

Measures of passive MTU stiffness provide insight into the ability of the passive structures of a MTU to resist stretch or deformation while under tensile load. As passive plantar-flexor stiffness was only weakly associated with passive DROM, it is not likely to be a substantial determinant of total ROM. We postulate that MTU stiffness may affect MTU strain type injury potential by allowing the MTU to either strain too far under a given load or by protecting some passive structures within the MTU at the expense of transferring load more readily to others. For example, the incidence of Achilles tendinopathy\(^{35}\) may be increased in Achilles tendons with low stiffness, which are consequently less able to resist elongation and therefore deform to injurious lengths, particularly where dorsiflexion ROM is not necessarily a limiting factor. Conversely, Achilles tendons with high stiffness may not be able to absorb sufficient strain energy to prevent other structures such as the muscle fibres from incurring excessive and injurious strains\(^{13}\). Due to the fact that strain type injuries to both tendon and muscular apparatus are thought to be more a factor of the actual strain and less dependent upon the magnitude of the tensile force\(^{35-37}\), it may be necessary for researchers to more thoroughly investigate the effects of MTU stiffness and not just joint ROM on joint mechanics in order to better understand MTU injury risk.

Although the present study did not assess the stiffness of individual MTU structures, such as the Achilles tendon, any discussion of plantar-flexor stiffness needs to consider the Achilles tendon. Achilles tendon stiffness has been strongly correlated with plantar-flexor stiffness\(^{38}\), possibly due to the fact that the Achilles tendon is the largest tendon in the human body\(^{39}\) and, therefore, the largest tendon offering resistance
during ankle dorsiflexion. It must also be noted, however, that the method for measuring passive torque and subsequently passive stiffness during ankle dorsiflexion in the present study, was assessing the passive resistance of the entire talocrural joint and not just the plantar-flexor MTU. This limitation was present in each of the passive DROM assessments, thereby allowing for a meaningful analysis of the relationships that exist between each of the measures of ankle ROM during passive dorsiflexion in the current study. Another limitation of the present study was that the passive stiffness tests, like the NWB DROM tests, were performed on the KinCom dynamometer, whereas the WB DROM tests were not performed on the KinCom. Nonetheless, the comparison between these test positions was necessary to provide an invaluable insight into the mechanical properties displayed during these different tests.

CONCLUSIONS

The weight-bearing and non-weight-bearing measures of passive ankle DROM were poorly correlated, with participants displaying significantly greater passive DROM while in the weight-bearing posture compared to the non-weight-bearing posture. This finding supports the notion that non-weight-bearing assessments of DROM may underestimate or even misrepresent the functional capacity of the talocrural joint to cope with dorsiflexion during dynamic weight-bearing tasks. Although non-weight-bearing assessments of DROM may be useful in assessing the effectiveness of rehabilitation for patients contraindicated for performing WB DROM assessments, they may not be useful in determining the ability of a patient or athlete to perform a weight-bearing task safely or effectively. Both DROM assessments were also poorly correlated with passive plantar-flexor stiffness, indicating that plantar-flexor stiffness may not be a strong determinant of DROM, irrespective of the posture used for assessment. Therefore,
although ankle DROM and plantar-flexor stiffness may be implicated in injury risk during dynamic weight-bearing tasks such as landing movements, it is likely due to different biomechanical mechanisms.

REFERENCES


PART II

Are ankle mechanics during drop landings affected by two different measures of plantar-flexor flexibility?
Chapter 3

Dorsiflexion capacity affects Achilles tendon loading during drop landings

This chapter is an amended version of the manuscript: Whitting JW, Steele JR, McGhee DE and Munro BJ. Dorsiflexion capacity affects Achilles tendon loading during drop landings. *Medicine and Science in Sports and Exercise*. Accepted for publication July, 2010.

ABSTRACT

Evidence suggests a link between decreased dorsiflexion range of motion (ROM) and injury risk during landings. The purpose of this study was to determine the effect of weight-bearing dorsiflexion ROM (DROM) on ankle mechanics during drop landings. Forty-eight males (22.5 ± 4.7 years) were measured for DROM. Participants performed drop landings onto a force platform at two vertical descent velocities (2.25 ± 0.15 m.s⁻¹ and 3.21 ± 0.17 m.s⁻¹), while EMG activity of four shank muscles and threedimensional ankle joint kinematics were recorded. Participants were classified into low (37.7 ± 2.5°) and high (48.4 ± 2.5°) DROM groups. Ground reaction force, EMG, dorsiflexion angle, plantar-flexion moment and Achilles tendon force (ATF) outcome variables were all equivalent for the two DROM groups during each landing condition. However, the low DROM group performed each landing condition at a significantly greater percentage of their DROM and displayed significantly more ankle eversion throughout most of the movement. The low and high DROM groups displayed DROM percentages of 27 ± 11 and 10 ± 11 (p = 0.013), 32 ± 9 and 23 ± 9 (p = 0.056), 60 ± 13 and 46 ± 13 (p = 0.004), 66 ± 16 and 54 ± 9 (p = 0.003) when they incurred the peak plantar-flexion moments, ATF, eversion angles and dorsiflexion angles, respectively.
Participants with a low DROM absorbed the landing impact forces with their plantar-flexor muscle-tendon units (MTU) in a more lengthened and everted position. Athletes with a low DROM may be more likely to regularly overload their plantar-flexor MTU, thereby potentially exposing themselves to a higher likelihood of incurring injuries such as Achilles tendinopathy.

INTRODUCTION

Range of motion (ROM) in dorsiflexion can determine the ability of an individual to perform fundamental weight-bearing tasks such as gait, negotiating stairs and landing movements. Landing tasks in sporting activities, however, place high demand on structures of the ankle joint because the dorsiflexion ROM used during each landing must absorb and dissipate the high ground reaction forces encountered upon ground contact. Landing movements typically involve higher impact velocities than gait tasks, ranging from 2.0 m.s\(^{-1}\) to over 6.0 m.s\(^{-1}\), which result in average peak ground reaction forces of between 2.6 and 18 times body weight (BW). As such, landing movements require rapid deceleration of the body’s momentum as the entire lower limb, beginning with the ankle joint, acts in a coordinated multi-joint fashion.

Ankle injuries account for up to 25-30% of all sporting injuries, with athletes at a high risk of sustaining an ankle sprain, fracture or musculotendinous injury during landing sports. Furthermore, musculotendinous overuse injuries account for as many as 50% of all sporting injuries, with the Achilles tendon, in particular, commonly injured in repetitive landing sports such as basketball and netball. Researchers suggest that landings which involve large or excessive joint excursions may place individuals at a high risk of incurring soft tissue injuries. Conversely, stiff landings that involve a limited amount of lower limb joint flexion are thought to use the ankle plantar-flexors
and passive structures to absorb an increased proportion of the forces encountered from foot-ground impact\textsuperscript{4, 15, 16}. Whether the plantar-flexors are lengthened too much from excessive dorsiflexion under load, or are overloaded during the energy absorption phase in a landing movement, athletes are clearly at risk of sustaining soft tissue injuries such as Achilles tendinopathy, particularly when overload or repetitive strain occurs toward the end of the physiological range of the tendon\textsuperscript{14}.

Although researchers have suggested a link between decreased dorsiflexion ROM and a variety of injuries such as ankle sprains and fractures and Achilles tendon overuse injuries\textsuperscript{14, 17, 18}, the mechanisms for any such links are not well understood. Moseley et al.\textsuperscript{2} demonstrated that individuals with decreased passive dorsiflexion ROM used less dorsiflexion ROM during the relatively slow eccentric task of descending stairs. These researchers also reported that the decreased dynamic ROM exhibited by individuals with less passive ROM, was coupled with a significantly greater internal plantar-flexion moment about the ankle\textsuperscript{2}, thereby inferring that greater loads may have been imposed upon the plantar-flexor complex. Furthermore, researchers suggest that individuals increase total ankle ROM in response to increases in landing velocity\textsuperscript{6}, possibly to mitigate increases in ground reaction force by plantar-flexing more at initial ground contact, without increasing the amount of ankle dorsiflexion\textsuperscript{6, 7}. However, no research has investigated the effects of passive dorsiflexion ROM on ankle mechanics at commonly incurred, albeit more dynamic landing velocities and, due to the high prevalence of ankle and plantar-flexor muscle-tendon injuries in landing sports, a more definitive investigation of how dorsiflexion ROM affects landing mechanics at different impact velocities is required. Therefore, the purpose of this study was to determine the effect of weight-bearing dorsiflexion ROM (DROM) on ankle joint mechanics during landings performed at different vertical descent velocities. We hypothesised that
individuals with low DROM would display less dorsiflexion and incur higher ground reaction forces and higher plantar-flexor loads than individuals with high DROM, at both landing velocities.

METHODS

Participants and DROM measure

Forty eight physically active males (mean age = 22.5 ± 4.7 years; height = 180.4 ± 7.4 cm; mass = 74.7 ± 10.9 kg) participated in this study. All participants were recruited from within the student and staff population of the University of Wollongong. Prior to participating, each recruit completed a ‘Physical Activity Readiness Questionnaire’19, a separate injury history questionnaire and a written informed consent form. Only those recruits who had no contraindications for completing the experimental protocol were included as participants. Ethical clearance for the study was obtained from the University of Wollongong Human Research Ethics Committee (HE06/333).

Prior to performing the DROM and drop landing protocols the test limb for each participant was determined by a functionally relevant limb dominance test, whereby each participant was asked to drop from a height of 32 cm and land on their preferred foot. The DROM of each participant was then quantified while participants performed a standing lunge test, previously shown to have high intra- and inter-rater reliability20. The standing weight-bearing test of DROM was selected due to its functional relevance to the closed kinetic chain nature of landing movements and because it provides a clear indication of the capacity of the talocrural joint, and essentially the entire ankle/foot complex, to dorsiflex20. All measurements were performed by the chief investigator [JWW] to avoid inter-rater variability and pilot testing with six subjects performing four
trials for each leg on three separate days, revealed a high reliability coefficient, irrespective of the leg measured (ICC > 0.97).

Participants performed the standing lunge while stabilizing themselves with their hands against a wall. They were instructed to maintain their hips and shoulders in an orientation that was parallel with the plane of the wall. The test limb was the forward leg and was assessed while the knee was flexed and the centre of the knee was aligned with a vertical line marked clearly on the wall. The subtalar joint was maintained in a standardised position by placing the foot on a line, marked on the floor, and perpendicular to the vertical line on the wall. The hallux and the centre of the heel were positioned directly on the line on the floor and the maximum DROM angle was measured using a Gollehon extendable goniometer (Model 01135; Lafayette Instrument Co., USA) when participants reached their self-selected stretch limit (see Fig. 2, Chapter 2). Each participant was instructed to stretch to their limit without inducing abnormal pain and measurements were only taken while participants maintained heel-ground contact (verified visually by a research assistant). Preceding this measure, marks were placed on the lateral malleolus and the lateral femoral condyle and the angle made by the intersection of the line between these two points and the floor, was recorded as the ankle flexion angle (see Fig. 2, Chapter 2). This measurement procedure was performed four times with the smallest ankle flexion angle being subtracted from 90° to give the actual value for maximum DROM capacity.

Following DROM assessment, the 48 participants were ranked from the lowest to highest DROM (°). The 15 participants with the middle DROM values were then removed from any further analysis to enable two distinct participant groups to be formed: a high DROM group (HDROM; mean = 48.4 ± 2.5°; range = 46° to 55°) and a low DROM group (LDROM; mean = 37.7 ± 2.5°; range 33° to 40°; p < 0.001). The
mean height (181.4 ± 4.6 cm and 181.5 ± 7.3 cm; \( p = 0.980 \)), body mass (73.6 ± 8.4 kg and 76.2 ± 11.5 kg; \( p = 0.463 \)) and age (22.5 ± 4.2 years and 22.7 ± 4.6 years; \( p = 0.891 \)) did not differ significantly between the LDROM and HDROM groups, respectively.

**Drop landing protocol**

To examine the effects of DROM on ankle mechanics during a controlled landing movement designed to induce plantar-flexor MTU strain in a relatively consistent manner, participants were instructed to perform a series of single limb drop landings at two distinct vertical descent velocities (slow: \( 2.25 \pm 0.15 \text{ m.s}^{-1} \) and fast: \( 3.21 \pm 0.17 \text{ m.s}^{-1} \)). All drop landings were performed from a custom-designed staircase with a safety handrail and easily adjustable platform heights. Participants were instructed to lead with their dominant landing limb and allow themselves to free-fall to land onto their dominant foot within the confines of the force platform. All participants were required to perform five successful trials from heights of 32 cm and 72 cm, resulting in the two distinct vertical landing velocities.

**Muscle activity**

EMG recordings were taken from tibialis anterior (TA), soleus (SO), gastrocnemius medialis (MG) and gastrocnemius lateralis (LG). The surface electrode sites were located according to the recommendations of Cram et al.\(^1\) and were confirmed by manually palpating the centre of each muscle belly. After standard skin preparation to reduce electrical impedance, silver/silver chloride surface electrodes (Ambu Blue Sensor N-00-S; Medicotest, Ølstykke, DEN) were aligned parallel with the direction of the muscle fibres and with an inter-electrode spacing of 22 mm. The reference electrode was placed over the tibial tuberosity. The EMG signals were relayed from the electrodes to a Telemyo 900 battery-powered transmitter (Noraxon, Scottsdale,
AZ), firmly secured to the back of each subject, and then to a Telemyo 900 receiver via an antenna and sampled at 1000 Hz (bandwidth 16-500 Hz).

The EMG signals were processed according to the guidelines endorsed by the International Society of Electrophysiology and Kinesiology\textsuperscript{22}. Firstly, the raw EMG signals were filtered using a fourth-order zero-phase-shift Butterworth filter (high-pass; frequency cut-off ($f_c$) = 15 Hz) to eliminate any movement artifact. To quantify the temporal characteristics of the muscle bursts, the filtered EMG data were then full-wave rectified and filtered again using a fourth-order zero-phase-shift Butterworth low-pass filter ($f_c = 20$ Hz). This processing technique produced a smoothed representation of the raw EMG signals and also retained the signals’ critical temporal characteristics\textsuperscript{6}.

Individual linear envelopes representing each muscle burst were then analysed to determine muscle burst onset, offset and peak amplitude. Following extensive pilot testing, a previously reported threshold, corresponding to 8\% of the peak amplitude of the linear envelope representing the muscle burst of interest\textsuperscript{6} was deemed optimal for the detection algorithm to identify onset and offset. The muscle activity analysed for each landing was the muscle burst that had its onset immediately prior to initial foot-ground contact (IC). This was deemed to represent the activity required to absorb the initial impact during the first and most critical phase of the landing when the participants were dorsiflexing their ankles. Each individual muscle’s raw and filtered EMG signals were then visually inspected to confirm the validity of the computer-generated markers to minimise the probability of any processing errors\textsuperscript{23, 24}. The temporal variables calculated for each trial included muscle burst onsets, offsets and peak amplitudes, relative to IC. All EMG outcome variables were determined at the same frequency as the ankle kinematics and kinetics ($f_c = 200$ Hz), as this rate was deemed to capture the true temporal characteristics of each muscle burst with sufficient
accuracy (measurement error = ± 5 ms), while enabling a direct comparison with the ankle mechanics outcome variables.

Ground reaction forces

The ground reaction force (GRF) data generated by each subject at IC were recorded using a Kistler multichannel force platform (Type 9281B, Kistler Instrumente AG Winterthur, Switzerland; 600 mm x 400 mm). The force platform was covered with a 12 mm thick layer of EVA rubber, which was adhered to a 10 mm thick compressed timber board, securely bolted to the platform. Although cushioned landing surfaces may affect the normative validity of force data\textsuperscript{25}, researchers have accepted that this limitation is a necessary safety provision when investigating landings associated with forces of the magnitude described in this study\textsuperscript{3,6}.

All GRF data were sampled at 1000 Hz for each successful trial. The four vertical, two anteroposterior, and two mediolateral GRF channels were summed to obtain force-time curves in the three orthogonal planes, as well as the resultant ground reaction force for each individual trial. The raw GRF data were filtered using a fourth-order zero-phase-shift Butterworth low-pass filter ($f_c = 100$ Hz). The time of IC, the peak vertical GRF (VGRF) and the time to reach VGRF from the moment of IC were then calculated in Newtons (N), as well as normalised for participant body weight (BW).

Kinematics and joint kinetics

Anatomical coordinates defining the foot and shank segments were sampled in three dimensions at 200 Hz using an OptoTRAK 3020 motion capture system (Northern Digital Inc., Waterloo, Canada) while participants performed the drop landings. Data from each marker (Fig. 7) were then passed through a fourth-order zero-phase-shift Butterworth low-pass filter ($f_c = 15$ Hz). A 15 Hz low-pass cut-off was deemed appropriate following a residual frequency analysis of the coordinate data. For the sole
purpose of calculating ankle joint kinetics, the raw GRF data were smoothed with the same low-pass filter as the position data ($f_c = 15$ Hz) and then used as input for an inverse dynamics solution. Research suggests that filtering kinematic and GRF data at the same frequency when calculating joint dynamics is essential for minimizing impact peak errors. All EMG, kinematic and kinetic data processing and analyses were conducted using Visual3D software (C-Motion, Inc., Germantown, MD; Version 4.00.15).

For the sole purpose of determining the amount of DROM utilised during the landing protocol, the angle between the sole of the foot and the shank segment was determined as a separate virtual ankle angle. The segment depicting the sole of the foot was modelled by projecting the medial and lateral foot markers (Fig. 7) onto the floor using coordinate data collected during static stance trials. A Pearson product moment correlation was then performed to compare the sagittal plane total ankle ROM calculated by using the virtual foot segment and original foot segment models and their corresponding ankle joints using the data from all 48 participants. The results revealed a very strong correlation between both ankle models at the slow and fast vertical descent velocities ($r = 0.992$ and $r = 0.975$, respectively). Therefore, the authors deemed the virtual ankle angle data to be reliable for the purposes of this study.

**Figure 7:** Anatomical sites used to define the foot and shank segments in Visual3D software. Dynamic markers: 1. 2$^{nd}$ metatarsal distal head, 2. 5$^{th}$ metatarsal distal head, 3. 1$^{st}$ metatarsal proximal head, 4. 5$^{th}$ metatarsal proximal head, 5. Lateral calcaneus, 6. Lateral malleolus, 7. Distal/posterior calcaneus, 8. Medial calcaneus, 9. Medial malleolus, 10. Mid anterior tibia, 11. Lateral femoral condyle, 12. Medial femoral condyle. Static markers: 13. 1$^{st}$ metatarsal distal head, 14. Proximal/posterior calcaneus.
Using the virtual ankle model we calculated the plantar-flexion angle at IC and the peak dorsiflexion angle achieved during the landing phase (Tab. 1). Using an ankle model created from static coordinate data described in Fig. 7, we also calculated dorsiflexion angular velocities, internal plantar-flexion moments, ankle eversion angles and Achilles tendon forces (ATF). The time taken from IC to reach peak dorsiflexion and peak ATF were also calculated (Tab. 1). Achilles tendon forces were calculated by dividing the internal plantar-flexion moment by the Achilles tendon moment arm as described by Self & Paine. Prior to conducting any statistical analyses, the internal plantar-flexion moments were normalised to body mass and the ATF were normalised to each participant’s body weight. Finally, calculations were also made to determine the amount of dorsiflexion displayed by each participant at critical events during the landing phase and these angles were expressed as percentages of each participant’s DROM.

Statistical analyses

All data sets were tested for normality using the Kolmogorov-Smirnov statistic with a Lilliefors significance correction. A two-way ANOVA (DROM group x vertical descent velocity) was then used to determine whether there were any significant main effects of DROM or descent velocity on the ankle mechanics outcome variables. An alpha level was set at 0.05 for all statistical analyses and all data were analyzed using SPSS for Windows (v. 17, SPSS Inc., Chicago, IL) and were expressed as mean ± SD throughout.

RESULTS

Electromyography

The two-way ANOVA revealed no significant interactions and no significant main effect of DROM group on any of the EMG outcome variables. Furthermore, there
was no significant effect of vertical descent velocity on the timing of the peak amplitude for any of the muscles sampled, with the pooled peak amplitudes for TA, SO, MG and LG relative to IC occurring at 158 ± 70 ms, 96 ± 56 ms, -43 ± 32 ms and 26 ± 79 ms, respectively. There was, however, a significant main effect of landing velocity on muscle onsets, with a significantly earlier recruitment pattern for all muscles during the fast landings (Fig. 8). The timing of muscle offsets remained consistent for TA, SO and LG with MG remaining activated for significantly longer, post IC, during the fast landings (Fig. 8).

![Figure 8: Mean (± SD) data pooled across DROM groups, representing the effects of vertical descent velocity on muscle burst onsets and offsets during the slow (2.25 m.s⁻¹) and fast (3.21 m.s⁻¹) drop landings. IC = Initial ground contact; TA = tibialis anterior; SO = soleus; MG = medial gastrocnemius; LG = lateral gastrocnemius. *p* < 0.05 indicates a significant difference.](image)

**Kinetics and kinematics**

The GRF, kinematic and kinetic outcome variable means (± SD) for the two DROM groups at the two vertical descent velocities are shown in Table 1. There were no significant DROM-descent velocity interactions for any of the GRF, kinematic or kinetic variables analyzed in this study. Although there was no main effect of DROM group on any of the GRF outcome variables, as expected the participants generated a significantly greater VGRF at a significantly faster rate during the fast landings than during the slow landings (Tab. 1).
Table 1: Mean (± SD) values for ground reaction force, kinematic and kinetic data, representing the effects of DROM group and the effects of vertical descent velocity during the slow (2.25 m.s\(^{-1}\)) and fast (3.21 m.s\(^{-1}\)) drop landings.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Group effect</th>
<th>Velocity effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LDROM N=16</td>
<td>HDROM N=17</td>
</tr>
<tr>
<td>Peak VGRF (N)</td>
<td>4002 (905)</td>
<td>4110 (780)</td>
</tr>
<tr>
<td>Peak VGRF (BW)</td>
<td>5.6 (1.2)</td>
<td>5.5 (0.9)</td>
</tr>
<tr>
<td>Time to reach peak VGRF (ms)</td>
<td>43 (11)</td>
<td>42 (9)</td>
</tr>
<tr>
<td>PF angle at IC (°)</td>
<td>21.0 (6.6)</td>
<td>21.7 (6.7)</td>
</tr>
<tr>
<td>Peak DF angle (°) ac</td>
<td>24.9 (4.0)</td>
<td>26.2 (4.6)</td>
</tr>
<tr>
<td>Time to reach peak DF angle (ms)</td>
<td>244 (76)</td>
<td>268 (82)</td>
</tr>
<tr>
<td>Peak DF angular velocity (°.s(^{-1}))</td>
<td>921 (140)</td>
<td>922 (155)</td>
</tr>
<tr>
<td>Peak PF moment (N.m.kg(^{-1}))</td>
<td>2.5 (0.2)</td>
<td>2.5 (0.4)</td>
</tr>
<tr>
<td>Peak ATF (BW)</td>
<td>5.0 (0.5)</td>
<td>5.0 (0.8)</td>
</tr>
<tr>
<td>ATF at peak DF angle (BW) bd</td>
<td>3.5 (0.6)</td>
<td>3.4 (0.8)</td>
</tr>
<tr>
<td>Time to reach peak ATF (ms)</td>
<td>61 (40)</td>
<td>55 (22)</td>
</tr>
<tr>
<td>Peak eversion angle (°)</td>
<td>15.7 (5.1)</td>
<td>12.5 (6.4)</td>
</tr>
<tr>
<td>Eversion angle at peak DF (°)</td>
<td>14.3 (5.0)</td>
<td>10.1 (6.1)*</td>
</tr>
<tr>
<td>Eversion angle at peak PF moment (°)</td>
<td>7.4 (5.4)</td>
<td>3.9 (5.0)</td>
</tr>
<tr>
<td>Eversion angle at peak ATF (°)</td>
<td>8.4 (5.6)</td>
<td>4.6 (5.1)*</td>
</tr>
</tbody>
</table>

VGRF = vertical ground reaction force; BW = body weight; IC = initial ground contact; PF = plantar-flexion; DF = dorsiflexion; ATF = Achilles tendon force. Reduced sample sizes for HDROM group: a N =16; b N = 14. Reduced sample sizes for velocity main effect: c N = 32; d N = 31. p < 0.05 indicates a significant difference. *p < 0.05; **p < 0.001.

The peak ankle dorsiflexion angles and the times taken from IC to reach peak dorsiflexion by all participants during the drop landings, revealed a very consistent dorsiflexion pattern for the entire sample, irrespective of DROM group or vertical descent velocity. However, although consistent between the DROM groups, the values for plantar-flexion at IC, peak dorsiflexion angular velocity, peak plantar-flexion moment and peak ATF were all significantly greater during the fast landings compared to the slow landings (Tab. 1). Interestingly, the pooled participant cohort encountered their peak ATF significantly earlier during the fast landings than during the slow landings, with no significant main effect of DROM group on this outcome variable (Tab. 1). Conversely, each of the ankle eversion outcome variables were unaffected by vertical descent velocity, albeit influenced by DROM group. As such, the eversion
angles at the time of the peak ATF and peak dorsiflexion were significantly larger for the LDROM group than they were for the HDROM group (Tab. 1).

**DROM percentages**

The percentages of DROM capacity utilised by participants in the LDROM group were significantly greater than those for the HDROM group at three of the four critical kinematic and kinetic events analysed in this study (Fig. 9). Although demonstrating a non-significant result, DROM percentage at the moment of peak ATF displayed a clear trend towards significance \( p = 0.056 \), with mean (+ SD) values again being larger for the LDROM group when compared with the HDROM group (Fig. 9). Furthermore, there were no significant DROM-descent velocity interactions for any of the data representing DROM percentages. Unlike the other kinematic and kinetic outcome variables analyzed in this study, however, none of the values representing percentages of DROM capacity were significantly affected by vertical descent velocity.

![Figure 9: Mean (+ SD) ankle dorsiflexion angles as a percentage of DROM at critical events. Data are pooled across both vertical descent velocities to represent the effect of DROM group on DROM percentages. \( p < 0.05 \) indicates a significant difference.](image-url)
DISCUSSION

In order to make a meaningful assessment of the effects of DROM on ankle mechanics during single limb drop landings, it is essential that each group genuinely represent a unique sample of participants with respect to the DROM measures. The difference in DROM values between the LDROM and HDROM groups in this study were statistically significant, thereby ensuring a clear distinction between the two groups. Furthermore, the range of DROM values in the present study is consistent with results published by other researchers using similar weight-bearing measurement techniques and similar cohorts\textsuperscript{17, 20, 28}, making the DROM data presented here both clinically significant and functionally relevant.

The fact that the LDROM and HDROM participants displayed almost identical characteristics for ankle neuromechanics, under two different landing conditions, suggests that the movement was determined more by the effects of gravity on the demands of the task, than by DROM capacity. Consequently, the LDROM group used more of their available DROM at every phase of the landing. This is very clearly illustrated in Figure 9, which shows the LDROM group used a significantly greater percentage of their DROM capacity at the times of the peak plantar-flexion moment, peak ankle eversion angle and the peak dorsiflexion angle. Furthermore, although not found to be statistically significant in this study, there was also a trend towards a higher percentage of DROM being utilised by the LDROM group at the moment of peak ATF during both landing conditions (see Fig. 9). As such, the LDROM subjects were placing their plantar-flexor muscle-tendon units in a more lengthened position than the HDROM group at critical events during ankle dorsiflexion and would likely have placed their Achilles tendons, in particular, under strain at more compromising lengths.
The additional ankle eversion displayed by the LDROM group during the single limb drop landings only further highlights the increased injury potential displayed by these more inflexible participants. The eversion angles displayed by our participants were consistent with findings by other researchers\textsuperscript{29-31}. Similar to the peak dorsiflexion angles, eversion angles throughout the landing movement were not found to be significantly affected by vertical descent velocity. The consistency in ankle flexion angles within the sagittal and coronal rotational planes further emphasises the effect of the high demands of the task on ankle rotation during the landing movement in the present study, rather than DROM capacity. Nonetheless, the LDROM group tended to evert their ankles more during both fast and slow landings than the HDROM group, with significant between-group differences occurring at the time of the peak ATF and peak dorsiflexion. The additional eversion displayed by the LDROM group is of particular concern, as evidence suggests there may be a link between excessive ankle eversion during weight acceptance and Achilles mid-portion tendinopathy in runners\textsuperscript{32}.

It is widely accepted that overuse injuries such as Achilles tendinopathy occur from overloading the tendon, causing micro-trauma to the lengthened collagen fibres\textsuperscript{14}. This may occur from repetitive overloading or may even occur more acutely when a non-uniform or abnormal stresses or strains are applied to localised fibres\textsuperscript{33}. The results of this study, therefore, support evidence which suggests that a decreased dorsiflexion capacity is associated with an increased risk of sustaining Achilles tendon injuries\textsuperscript{14, 18}, particularly as Achilles tendon injuries are commonly incurred during repetitive landing sports such as basketball and netball\textsuperscript{11}. While the landing protocol in the present study was highly controlled, it is apparent from the literature that a number of the characteristics which determined ankle neuromechanics here are commonly adopted by athletes in various types of landings and may simply be a function of the task\textsuperscript{3, 4, 8, 16, 34}. 
As the ankle is the first major joint to absorb the external landing forces, the plantar-flexor muscle-tendon unit must dissipate the loads it encounters very quickly.

Regardless of DROM capacity, muscle activation patterns displayed during the drop landing protocol were very similar between the participant groups. Humans use a pre-programmed feed-forward strategy to set ankle joint stiffness when performing landing movements in anticipation of the impending load\(^35\). This requires a coordinated activation of the muscles surrounding the talocrural joint before and after IC, in order to keep the peak dorsiflexion angle within physiological limits\(^35\). It is widely accepted that joint stiffness of the entire lower limb tends to be moderated by the demands of an activity, with more resistance being required as impact velocity increases\(^9\). The similarities in peak dorsiflexion angles between the LDROM and HDROM groups and the amount of time taken to reach peak dorsiflexion in this study, irrespective of a significant increase in vertical descent velocity, dorsiflexion angular velocity and peak VGRF, supports this notion. The values for muscle onsets and offsets reported for this study are consistent with previous research\(^6, 23, 34, 35\), although until now, no study has examined these activation patterns as they relate to any measure of the ankle’s physiological capacity to dorsiflex.

The similarity in neuromuscular activation patterns between the LDROM and HDROM groups must, to some extent, account for the similarities in ankle joint mechanics and, subsequently, the VGRF and kinetic forces experienced by all participants (Tab. 1). As landing on a single limb involves controlling the body’s downward momentum with less musculature than double limb landings, single limb landings tend to be hard or stiff according to accepted landing terminology and principles\(^9, 15, 16\). That is, stiff landings are usually associated with less knee flexion, higher VGRF and more load absorption by the plantar-flexors\(^4, 16\). The peak VGRF
encountered during the single limb drop landings in this study are comparable with values reported for other single limb landings\textsuperscript{15, 36}, as well as double limb landing protocols such as those performed by gymnasts or parachutists that may be characterised as hard or stiff\textsuperscript{6, 7}.

The similar neuromuscular and GRF profiles exhibited by the LDROM and HDROM groups were also reflected in other outcome variables describing ankle joint mechanics, such as peak dorsiflexion angle and peak dorsiflexion angular velocity. It is reasonable to postulate, therefore, that the consistency in dorsiflexion strategy used during fast and slow landings may be due to the increased internal plantar-flexion moment, shown to be approximately 50\% in this study, which is required to resist the external dorsiflexion moment experienced during landings\textsuperscript{3, 7}. The peak internal plantar-flexion moments found in this study were well within a reasonably wide range of internal plantar-flexion moments reported in the literature, for a variety of comparable landing protocols\textsuperscript{3, 4, 7}.

Similarly, although slightly larger, the peak normalised ATF calculated in the present study are comparable with those determined by Self & Paine\textsuperscript{3} when their values were normalised for body weight. It should be noted, however, that the low drop height and the stiff knee protocol employed, for the most part, in the study by Self & Paine\textsuperscript{3}, may be responsible for slightly lower ankle moments and ATF. That is, when participants are allowed to self-select their landing strategy with greater knee flexion, more of the foot-ground impact may occur toward the toes, thereby naturally increasing the moment applied to the ankle\textsuperscript{3}. Nonetheless, it is clear that DROM did not affect the peak plantar-flexion moment, peak ATF or the time taken from IC to the peak ATF in the present study (Tab. 1). It is also apparent that the participants were subjected to the peak ATF very soon after IC and then were forced to sustain a substantial proportion of
the peak ATF for the remainder of the dorsiflexion movement (see Tab. 1 and Fig. 10).
Consequently, the LDROM group were forced to absorb their ATF, albeit similar in
magnitude, in a lengthened position and also had to sustain this load as their plantar-
flexor muscle-tendon units were lengthened significantly more than their HDROM
counterparts.

Figure 10: Typical Achilles tendon force (ATF) and ground reaction force (GRF) traces depicting the mean values for a single participant during fast (3.21 m.s\(^{-1}\)) vertical descent velocity drop landing trials. A = mean time for peak plantar-flexion moment; B = mean time for peak eversion angle; C = mean time for peak dorsiflexion angle.

The action of the triceps surae, through the Achilles tendon, produces plantar-
flexion and inversion forces, as well as providing up to 93% of the plantar-flexion
moment\(^{37}\). Although research has demonstrated that different muscles within the triceps surae make different contributions to the loads passing through the Achilles tendon\(^{38}\), such determinations are beyond the scope of the present study. Nonetheless, ankle eversion places the Achilles tendon in a more lengthened position and, if already under strain in a dynamic situation, it is reasonable to speculate that the ATF would be greater when eversion is accounted for. A limitation of the method used to calculate ATF in the present study is its two-dimensional nature. Although still very useful as an approximation of the load being transmitted through the plantar-flexor MTU, the sagittal plane calculation may have underestimated the ATF generated, particularly by a more everted ankle. Therefore, it is important to reiterate that the only kinematic
variables that displayed a tendency to be different between the groups were the eversion angles measured throughout the landing movement, thereby potentially adding to the load experienced by the Achilles tendons in the LDROM group.

Although the results of this research point toward a potential mechanism for soft tissue injury risk in athletes with a decreased DROM during landing movements, we were unable to draw any strong conclusions regarding an increased risk of more acute bony and ligamentous ankle injuries being associated with a low DROM. It should be noted that factors such as player contact, obstacles or poor technique may actually account for many ankle sprains and fractures\textsuperscript{13, 39, 40}. Nonetheless, researchers have suggested that minimal joint excursions in the lower limb, constituting stiff landings usually associated with higher GRF\textsuperscript{3, 9, 16}, may result in bony type injuries as these tissues are loaded too quickly and beyond their physiological absorptive capacity. Although the LDROM group appears to operate at a lengthened muscle-tendon range, the consistency in most of the other landing characteristics suggests that they may be at no more risk of an ankle sprain or fracture during landing velocities of the magnitude tested in this study. However, as individuals such as gymnasts and parachutists tend to perform very stiff landings at high vertical descent velocities, a low DROM may potentially expose them to more acute bony and ligamentous injuries if they are operating in a vastly lengthened musculotendinous state. This notion requires a more thorough investigation using an experimental protocol that provides for a wider range of vertical descent velocities.

**CONCLUSIONS**

Despite a large difference in dorsiflexion capacity between the LDROM and HDROM groups and in contrast to our hypotheses, there were very similar results between the groups for most of the drop landing outcome variables, irrespective of
vertical descent velocity. As such, we conclude that landing strategies displayed by the participants in this study were moderated more by the demands of the task itself than they were by the ROM available at the talocrural joint. The implications for injury potential in athletes with a low functional DROM are that these athletes may often be forced to absorb landing loads by the plantar-flexor muscle-tendon unit at extended and therefore physiologically compromised lengths. This may expose these athletes to an increased risk of both acute and repetitive overuse strain injuries such as Achilles tendinopathy, an injury risk exacerbated when these athletes use a greater range of ankle eversion as part of their dorsiflexion strategy. Further research is required, however, to investigate the contribution of other plantar-flexor strength and flexibility characteristics to ankle mechanics during landings, in order to more completely understand the mechanisms for injury potential proposed in this study.

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Chapter 3


Chapter 4

Effects of passive plantar-flexor stiffness on ankle mechanics during drop landings

This chapter is an amended version of the manuscript: Whitting JW, Steele JR, McGhee DE and Munro BJ. Effects of passive plantar-flexor stiffness on ankle mechanics during drop landings. British Journal of Sports Medicine. Submitted for publication December, 2010.

ABSTRACT

Both low and high plantar-flexor stiffness have been implicated in increased injury risk during landing activities, yet no research has systematically investigated the effects of passive plantar-flexor stiffness on lower limb mechanics during landing. Therefore, this study aimed to determine how passive plantar-flexor stiffness affected loading of the plantar-flexor MTU during drop landings. Passive plantar-flexor stiffness and passive dorsiflexion range of motion (DROM) were quantified for 42 males. Participants were grouped as having low (LPS: 0.94 ± 0.15 Nm.°⁻¹) or high (HPS: 2.05 ± 0.36 Nm.°⁻¹; \( p < 0.001 \)) passive plantar-flexor stiffness. Three-dimensional ankle joint kinematics were quantified while participants performed drop landings onto a force platform (slow: 2.25 ± 0.16 m.s⁻¹; fast: 3.21 ± 0.17 m.s⁻¹). There was no significant difference between the groups for DROM (LPS: 43.9 ± 4.1°; HPS: 42.5 ± 5.7°), indicating that landing mechanics were not influenced by ankle range of motion. There were also no significant effects of passive plantar-flexor stiffness on any of the outcome variables characterising ankle mechanics during drop landings, including peak dorsiflexion and eversion angles, angular ankle flexion velocity, ground reaction forces, internal plantar-flexion moments or Achilles tendon forces. Neither high nor low passive plantar-flexor stiffness was found to influence ankle biomechanics during drop
landings. Landing strategies were moderated more by the demands of the task than by passive plantar-flexor stiffness. This suggests that passive plantar-flexor stiffness may not affect plantar-flexor strain injury risk during a simple drop landing task.

INTRODUCTION

During landings tasks, external forces are absorbed rapidly, loading extensor mechanisms such as the plantar-flexor muscles\textsuperscript{1-3}. Although landing tasks require a multi-joint strategy to dissipate ground reaction forces through the entire lower limb\textsuperscript{4}, the ankle is the first major joint to be exposed to these external loads. Force dissipation through rapid eccentric lengthening of the plantar-flexor muscle-tendon unit (MTU), to decelerate the lower limb,\textsuperscript{5} exposes both the Achilles tendon and the muscle fibres of the triceps surae to the risk of incurring acute and overuse injuries\textsuperscript{6-8}. Acute and overuse strain injuries are the most common of all sporting injuries, with Achilles tendinopathies and gastrocnemius muscle strain injuries being among the most prevalent\textsuperscript{6, 8, 9}, particularly in sports involving explosive stretch shortening cycle or eccentric movements such as jumping and landing\textsuperscript{7, 10-12}.

Retrospective and epidemiological studies suggest an association between a low passive dorsiflexion range of motion (DROM) and plantar-flexor MTU strain injuries during movements, such as landings, that dorsiflex the ankle and lengthen the plantar-flexor MTU\textsuperscript{9, 13}. Although the biomechanics of this increased risk of injury are not well understood, reduced DROM in both elderly and young adult male populations has been shown to alter gait and balance strategies, possibly increasing loads about the ankle\textsuperscript{14, 15}. Young healthy males with low DROM have also been found to land with their plantar-flexor MTU in a more lengthened and strained position compared to their high DROM counterparts\textsuperscript{16}. Low DROM may lead to greater strain by loading plantar flexor MTU
structures, such as the Achilles tendon and gastrocnemius muscle bellies, while more lengthened. Muscle strain injuries have been suggested to be more a factor of strain than the magnitude of force\textsuperscript{10, 17} and similarly, the risk of incurring a tendon injury is thought to be particularly high when the overload or repetitive strain occurs towards the end of the normal range of the tendon\textsuperscript{9, 18}.

Another aspect of plantar-flexor flexibility is the passive compliance of the MTU, typically determined by measures of stiffness or resistance to stretch\textsuperscript{19, 20}. Although the resistance of the plantar-flexor MTU to stretch has been used to assess dorsiflexion range of motion,\textsuperscript{14} there is some evidence to suggest that plantar-flexor stiffness and DROM may be poorly correlated and therefore affect ankle biomechanics and injury potential differently\textsuperscript{21}. Furthermore, the literature seems divided between possible associations with injury risk and MTU compliance. Witvrouw et al.\textsuperscript{7} postulated that a more compliant and energy-absorbent Achilles tendon would likely transfer less energy to the adjacent contractile apparatus, thereby providing some protection from muscle strain injuries during lengthening actions, such as those found in stretch shortening cycle activities. These authors also reasoned that, because more compliant tendons have been linked to better energy return and improvements in stretch shortening cycle performance\textsuperscript{22}, a more compliant tendon would be able to absorb more energy before becoming injured\textsuperscript{7}. The Achilles tendon, being the largest tendon in the human body\textsuperscript{11, 18}, is the most substantial tendinous structure in the ankle joint and, not surprisingly, Achilles tendon stiffness has been strongly correlated with plantar-flexor stiffness\textsuperscript{23}. Therefore, the conclusions of Witvrouw et al.\textsuperscript{7} regarding tendon compliance have strong implications for overall plantar-flexor MTU compliance and MTU strain injury risk.

In contrast, research demonstrates that ex-vivo Achilles tendons that strained further under an initial stress, thereby displaying greater compliance, failed sooner and
after fewer cycles than less compliant tendons displaying less initial strain. This indicates an association between a reduced capacity to resist stretch and a higher propensity for structural failure and injury risk and provides an alternative mechanical explanation for the widely-accepted notion that MTU injury is more a function of strain and not necessarily the magnitude of force. Much of the research supporting this notion, however, involves ex-vivo or isolated musculotendinous structures and any conclusions regarding the application of these findings to complex and in-vivo MTU mechanics must be made with caution. Nonetheless, it is reasonable to postulate that a more compliant MTU, displaying low measures of mechanical stiffness, may stretch further under a given tensile load, thereby overloading individual structures as they approach the end of their normal range. Accordingly, there is a duality in the evidence, with suggestions that both low and high plantar-flexor stiffness may be implicated in increased injury risk during lengthening dorsiflexion movements such as those experienced during landing activities. However, no research has systematically investigated the effects of passive plantar-flexor stiffness on ankle mechanics during a landing task. Therefore, the purpose of this study was to determine how passive plantar-flexor stiffness affected ankle mechanics and plantar-flexor loading during single limb drop landings. We hypothesised that individuals with high passive plantar-flexor stiffness would display significantly less dorsiflexion, incur significantly higher ground reaction forces and experience significantly greater plantar-flexor MTU loading during the drop landings.
METHODS

Participants

Forty two physically active males (mean age = 22.8 ± 5.0 years; height = 180.3 ± 7.8 cm; mass = 75.7 ± 10.9 kg) were recruited from within the campus population of the University of Wollongong to participate in the study. Prior to participating, each recruit completed injury history and ‘Physical Activity Readiness’ questionnaires and provided written informed consent. Recruits with any contraindications for completing the experimental protocol were excluded. Ethical clearance for the study was obtained from the University of Wollongong Human Research Ethics Committee (HE06/333).

The test limb was determined by asking each participant to drop from a height of 32 cm onto their preferred landing foot. The weight-bearing DROM for each participant’s test limb was then measured goniometrically (Gollehon extendable goniometer: Model 01135; Lafayette Instrument Co., USA) using a standing lunge test. Each participant performed a series of passive dorsiflexion movements while flexing the knee and maintaining a standardised hip, knee and ankle alignment in the other two planes. Pilot testing by the authors of the present study, involving six subjects performing four trials for each leg on three separate days, revealed a high reliability coefficient, irrespective of the leg measured (ICC=0.97, two-way mixed effects model for consistency of single measures).

Passive plantar-flexor stiffness

Passive plantar-flexor stiffness was measured using a KinCom isokinetic dynamometer (Kinetic Communicator, Chattecx Corp., Chattanooga, TN). Participants assumed a prone position on the dynamometer bench, with their foot firmly strapped to the dynamometer foot-plate. The lateral malleolus was aligned with the axis of rotation of the dynamometer head and, using a Gollehon extendable goniometer, the knee was
placed in a statically flexed position (10°), thereby taking the gastrocnemius muscle off full stretch. The ankle was rotated from 5° of plantar-flexion to their pre-determined stretch limit and participants were instructed to relax their ‘calf’ muscles and not actively resist the movement. The foot-plate was rotated slowly at a constant velocity of 5°.s⁻¹ in order to prevent muscular activation from stretch reflexes. Passive plantar-flexor stiffness was determined by measuring the slope of the torque-angle curve generated between 15° and 20° of dorsiflexion (see Fig 1, Chapter 2).

Analog data pertaining to the angular position, angular velocity and torque were sampled at 100 Hz directly from the KinCom PC via a National Instruments DAQpad 6015/1016 using MyoResearch XP collection software (Version 1.04.02, Noraxon Inc, Scottsdale, AZ). Electromyography (EMG) data were sampled from four shank muscles (see EMG methods) and synchronised with the KinCom output data using the same MyoResearch software. The raw EMG data were later inspected to confirm that the movements were passive and any trials involving visible muscle activation were excluded from further analysis.

Following passive plantar-flexor stiffness assessment, the 42 participants were ranked from the lowest to highest passive plantar-flexor stiffness (Nm.°⁻¹). The 10 participants with the middle passive plantar-flexor stiffness values were removed from any further analysis, leaving two distinct participant groups (n = 16 each): a low passive plantar-flexor stiffness group (LPS) and a high passive plantar-flexor stiffness group (HPS). Group descriptives, including DROM and anthropometric measures, are shown in Table 2.
Table 2: Mean (± SD) values for all descriptive variables characterising participants in the low (LPS) and high (HPS) passive plantar-flexor stiffness groups.

<table>
<thead>
<tr>
<th>Group descriptives</th>
<th>LPS n = 16</th>
<th>HPS n = 16</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plantar-flexor flexibility</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passive stiffness (Nm.°⁻¹)</td>
<td>0.94 (0.15)</td>
<td>2.05 (0.36)</td>
<td>-1.31 - -0.91 **</td>
</tr>
<tr>
<td>DROM (°)</td>
<td>43.9 (4.1)</td>
<td>42.5 (5.7)</td>
<td>-2.2 - 5.1</td>
</tr>
<tr>
<td>Anthropometrics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height (cm)</td>
<td>179.7 (6.2)</td>
<td>180.6 (8.2)</td>
<td>-6.1 - 4.4</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>76.4 (10.9)</td>
<td>73.3 (9.7)</td>
<td>-4.3 - 10.6</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>25.3 (6.3)</td>
<td>21.6 (3.7)</td>
<td>-0.1 - 7.4</td>
</tr>
</tbody>
</table>

** indicates a significant between-group difference (p < 0.001).

Drop landing protocol

To examine the effects of passive plantar-flexor stiffness on ankle mechanics during a controlled landing movement designed to strain the plantar-flexor MTU, participants performed a series of single limb drop landings from heights of 32 cm and 72 cm\textsuperscript{16}. The two distinct vertical descent velocities (slow: 2.25 ± 0.16 m.s\textsuperscript{-1} and fast: 3.21 ± 0.17 m.s\textsuperscript{-1}) were designed to cause significantly different loading stresses, thereby providing greater insight into mechanical responses by the LPS and HPS groups during different landing velocities. All drop landings were performed from a custom-designed staircase with easily adjustable platform heights and participants were instructed to lead with their test landing limb and free-fall to land onto their test foot. A trial was deemed successful when a participant landed with their foot within the confines of the force platform and all participants performed five successful trials per drop height.

Ground reaction forces

Ground reaction force data generated by each subject at initial foot-ground contact were recorded using a Kistler multichannel force platform (Type 9281B, Kistler Instrumente AG Winterthur, Switzerland; 600 mm x 400 mm; 1000 Hz). The top
surface of the force platform was covered with a 12 mm thick layer of EVA rubber, adhered to a 10 mm thick timber board and bolted to the platform. Although cushioned landing surfaces affect the normative validity of force data\textsuperscript{29}, researchers have accepted this limitation as a necessary safety precaution when investigating landing forces of high magnitude\textsuperscript{1, 30}. The four vertical, two anteroposterior and two mediolateral ground reaction force channels were summed to obtain force-time curves in the three orthogonal planes, as well as the resultant ground reaction forces for each individual trial. The raw ground reaction force data were filtered using a fourth-order zero-phase-shift Butterworth low-pass filter ($f_c = 100$ Hz). The peak vertical ground reaction force (VGRF) was calculated in Newtons (N) and then normalised for participant body weight (BW).

**Kinematics and joint kinetics**

Dynamic (2\textsuperscript{nd} metatarsal distal head, 5\textsuperscript{th} metatarsal distal head, 1\textsuperscript{st} metatarsal proximal head, 5\textsuperscript{th} metatarsal proximal head, lateral calcaneus, lateral malleolus, distal/posterior calcaneus, medial calcaneus, medial malleolus, mid anterior tibia, lateral femoral condyle, medial femoral condyle) and static (1\textsuperscript{st} metatarsal distal head, proximal/posterior calcaneus) infra-red markers were placed on anatomical sites used to define the foot and shank segments\textsuperscript{16}. Coordinate data from the dynamic markers were sampled in three dimensions (200 Hz; Opto\textsuperscript{TRAK} 3020, Northern Digital Inc., Waterloo, Canada) while participants performed the drop landings. Data from each infra-red marker were then low-pass filtered (Butterworth, fourth-order zero-phase-shift) at 15 Hz following the results of a residual frequency analysis. Dorsiflexion angular velocities, internal plantar-flexion moments, Achilles tendon forces (ATF) and eversion angles displayed throughout the landing were then calculated for each participant. To calculate ankle joint kinetics, raw ground reaction force data were
filtered at the same rate (15 Hz; low-pass) and used as input for an inverse dynamics solution, thereby minimising the possibility of impact peak errors\textsuperscript{31, 32}. ATF were calculated by dividing the internal plantar-flexion moment by the Achilles tendon moment arm using a regression equation developed by Self & Paine\textsuperscript{1}. All moments were normalised to body mass and the ATF were normalised to each participant’s body weight. All signal processing and analysis was performed using Visual3D software (V3D; C-Motion, Inc., Germantown, MD; Version 4.00.15).

Statistical analyses

All data sets were tested for normality using the Kolmogorov-Smirnov statistic with a Lilliefors significance correction. Independent \( t \)-tests were performed on the reduced group data sets describing plantar-flexor stiffness, DROM and anthropometric characteristics to examine the difference between the LPS and HPS groups. A two-way ANOVA (passive plantar-flexor stiffness x vertical descent velocity) was then used to determine whether there were any significant main effects of passive plantar-flexor stiffness or descent velocity, or any significant interactions, on the drop landing outcome variables. An alpha level was set at 0.05 for mean differences for all statistical analyses. All data were analysed using SPSS for Windows (SPSS Inc., Chicago, IL; Version 17) and expressed as mean (± SD) throughout.

RESULTS

No significant main effects of passive plantar-flexor stiffness on any of the ground reaction force, kinematic or joint kinetics outcome variables and no significant plantar-flexor stiffness x vertical descent velocity interactions were found (Tab. 3). Conversely, many of the ground reaction force, kinematic and kinetic outcome variables listed in
Table 3 were significantly affected by landing velocity, however, the peak dorsiflexion and eversion angles were not significantly different at either landing velocity.

**Table 3:** Mean (± SD) values for the ground reaction force, kinematic and kinetic data, representing the effects of passive plantar-flexor stiffness group and vertical descent velocity during the slow and fast drop landings.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Group effect</th>
<th>Velocity effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LPS (n = 16)</td>
<td>HPS (n = 16)</td>
</tr>
<tr>
<td>Peak VGRF (BW)</td>
<td>5.6 (1.1)</td>
<td>5.0 (1.0)</td>
</tr>
<tr>
<td>PF angle at IC (°)</td>
<td>21.7 (6.1)</td>
<td>23.9 (8.2)</td>
</tr>
<tr>
<td>Peak DF angle (°)</td>
<td>25.5 (3.6)</td>
<td>26.3 (5.2)</td>
</tr>
<tr>
<td>Peak DF angular velocity (°.s⁻¹)</td>
<td>909 (137)</td>
<td>968 (173)</td>
</tr>
<tr>
<td>Peak PF moment (N.m.kg⁻¹)</td>
<td>2.5 (0.4)</td>
<td>2.5 (0.3)</td>
</tr>
<tr>
<td>Peak ATF (BW)</td>
<td>4.8 (0.8)</td>
<td>5.0 (0.6)</td>
</tr>
<tr>
<td>ATF at peak DF angle (BW)</td>
<td>3.3 (0.7)</td>
<td>3.4 (0.6)</td>
</tr>
<tr>
<td>Peak eversion angle (°)</td>
<td>14.1 (6.9)</td>
<td>16.0 (6.0)</td>
</tr>
<tr>
<td>Eversion at peak DF (°)</td>
<td>11.9 (6.8)</td>
<td>14.3 (5.8)</td>
</tr>
<tr>
<td>Eversion angle at peak ATF (°)</td>
<td>6.1 (5.4)</td>
<td>8.3 (5.7)</td>
</tr>
</tbody>
</table>

VGRF = vertical ground reaction force; BW = body weight; IC = initial foot-ground contact; PF = plantar-flexion; DF = dorsiflexion; ATF = Achilles tendon force. Reduced sample sizes for LPS group: ¹ N =15; ² N = 14. Reduced sample size for HPS group: ³ N =15. Reduced sample sizes for velocity main effect: ⁴ N = 31; ⁵ N = 29. * indicates a significant between-condition difference (p < 0.05; ** p < 0.001).

**DISCUSSION**

The DROM values obtained in this study closely resemble values reported by others who have used similar cohorts and methods to assess DROM. Similarly, the mean passive plantar-flexor stiffness value (~1.4 Nm.°⁻¹) recorded by Kubo et al. from a 15° to 25° range of dorsiflexion, approximates the mean passive plantar-flexor stiffness value for our entire participant sample (1.48 ± 0.55 Nm.°⁻¹; N = 42), recorded from a range of 15° to 20° of dorsiflexion. When data for the 10 participants with the middle passive plantar-flexor stiffness values were removed from the entire cohort, the remaining LPS and HPS groups (Tab. 2) displayed clearly unique plantar-flexor stiffness characteristics, thereby offering a meaningful comparison of plantar-flexor mechanical responses to drop landing stimuli, albeit in a healthy population.
The LPS and HPS groups displayed almost identical ankle mechanics with very similar responses to the change in vertical descent velocity, as reflected in the internal plantar-flexor moments and the ATF displayed by the cohort (Tab. 3). Overall, the peak internal plantar-flexor moments reported in this study were consistent with previous research\(^1\)-\(^3\), increasing by close to 50% during the landings with fast vertical descent velocities\(^1\),\(^2\). In addition, although slightly larger than the ATF values reported by Self & Paine\(^1\), the normalised ATF values generated by healthy active males in the present study are comparable with ATF generated by healthy active males during single-legged hopping\(^3\(^4\). It is reasonable to postulate, therefore, that the ankle mechanics displayed during the drop landings performed in the present study were largely determined by the landing task itself and not necessarily by stiffness of the passive tissues in the plantar-flexor MTU. These results contrast with those of Moseley et al.\(^1\(^4\) who demonstrated that a greater passive resistance to stretch in dorsiflexion, produced a reduction in ankle dorsiflexion and an increase in the moment about the ankle during stair descents. This difference in findings may be due to the more demanding eccentric drop landing task, at both landing velocities, completed by participants in the present study, compared to a slow and controlled gait task in the study by Moseley et al.\(^1\(^4\), albeit a dynamic stimulus that lengthens the plantar-flexor MTU.

Ankle mechanics during single limb drop landings have been found to be unaffected by differences in DROM, although it was postulated that participants’ with low DROM absorbed their ATF with the plantar-flexor MTU in a significantly more lengthened position compared to participants with high DROM\(^1\(^6\). However, there was no between-group difference in DROM or in the dynamic dorsiflexion angle at the time of peak ATF in the present study, indicating that neither group experienced more plantar-flexor MTU strain than the other. Although ATF is a useful approximation of
the magnitude of the load transmitted through the plantar-flexor MTU via the Achilles tendon, it must be noted that the regression equation used to calculate the tendon moment arm assumes between-subject consistency, dependent upon changes in ankle flexion angles only. The two-dimensional equation for calculating ATF does not account for knee flexion or hindfoot eversion that may also influence plantar-flexor strain and, therefore, stress. The ATF calculation also assumes that the entire moment about the ankle is transmitted through the plantar-flexor MTU, when other structures may be involved in absorbing this load. Nonetheless, as there was no significant between-group difference in ankle eversion in the present study and because research has shown that the triceps surae may generate in excess of 90% of the plantar-flexion torque, use of this method as an estimation of plantar-flexor loading is justified.

It must be noted, however, that for a given length change of the plantar-flexor MTU, passive plantar-flexor stiffness in the HPS group was significantly greater than that of the LPS group (Tab. 2). Accordingly, it is reasonable to postulate that the magnitude of the internal stress encountered by the passive plantar-flexor tissues of the HPS group during the drop landings may have been affected by their inherent stiffness, particularly as the kinematic results indicate that each group achieved the same end range of motion in dorsiflexion during this dynamic loading movement. Therefore, although the effects of excessive plantar-flexor stiffness on potential injury mechanisms during landing tasks requires further investigation, the results of the present study do not indicate any increased risk of strain type injuries to the plantar-flexor MTU of a healthy and physically active population with low plantar-flexor passive stiffness. A limitation of the present study is the assessment of the effects of passive stiffness on a dynamic landing movement involving muscular activation. It must be acknowledged
however, that the stiffness of the activated plantar-flexor MTU during the landing task in the present study may have been augmented and, therefore, the magnitude of inherent stress experienced by each group may be of more importance than the magnitude of strain. Nonetheless, this argument remains speculative and requires further investigation.

Although a highly controlled landing protocol was used in the present study, the literature shows that many of the ground reaction force and plantar-flexor MTU loading patterns displayed by our participants are common to various types of landings, further emphasising the influence of task demands such as landing velocity, rather than plantar-flexor stiffness, on this dynamic movement\textsuperscript{1,3,4,37}. The present study demonstrated that increased vertical descent velocity and ground reaction forces resulted in significantly greater plantar-flexor loading in all participants, without significantly altering their ankle kinematics. Notwithstanding the limitations in our inverse dynamics calculation of plantar-flexor moments and subsequent calculations of ATF, it is reasonable to assume, therefore, that the consistency in kinematics and external loads may result in similar plantar-flexor loading patterns between the two groups.

**CONCLUSIONS**

Despite a large difference in passive plantar-flexor stiffness between the LPS and HPS groups, there were similar results between the groups for most outcome variables, irrespective of vertical descent velocity. The landing strategies displayed by the participants in this study, therefore, were moderated more by the task than by passive plantar-flexor stiffness. Each group also demonstrated a similar capacity to passively dorsiflex the ankle, strengthening the finding that neither group may have experienced a potentially more injurious magnitude of plantar-flexor MTU strain than the other.
Therefore, the results of the present study indicate that passive plantar-flexor stiffness does not significantly affect plantar-flexor strain injury risk during a simple drop landing task. Nonetheless, the notion that inherently higher passive plantar-flexor stiffness may increase plantar-flexor loading during a dynamic landing task, where plantar-flexor strain is unaffected, needs to be investigated further.

REFERENCES


Whitting JW, Steele JR, McGhee DE, & Munro BJ. Different measures of plantar-flexor flexibility and their effects on landing technique: Implications for injury.


PART III

How does training affect measures of plantar-flexor flexibility and will training moderate ankle mechanics during drop landings?
Chapter 5

Effects of three different training methods on plantar-flexor strength and flexibility: A randomised controlled trial

This chapter is an amended version of the manuscript: Whitting JW, Steele JR, McGhee DE and Munro BJ. Effects of three different training methods on plantar-flexor strength and flexibility: A randomised controlled trial. *Clinical Biomechanics*. Submitted for publication December, 2010.

ABSTRACT

Stretch and strength training may increase joint and muscle-tendon range of motion, although research regarding concomitant effects on muscle-tendon stiffness is conflicting. Furthermore, no researchers have assessed the effects of task-specific training, designed to provide a combined stretch and eccentric strength stimulus, on dorsiflexion range of motion. This study aimed to determine and compare the effects of static stretch, eccentric strength and landing-specific training on passive dorsiflexion range of motion and passive plantar-flexor stiffness. Dorsiflexion range of motion (DROM) and plantar-flexor stiffness and strength were assessed in 45 male volunteers before and after a 6-week training intervention, using a parallel assessor-blinded randomised trial. The three experimental training groups included static stretch (n = 10), eccentric strength (n = 12) and landing training (n = 11); and one control group (n = 12). Passive dorsiflexion range of motion significantly increased in the stretch (6° ± 4°; 15% increase; \( p = 0.003 \)) and eccentric strength training (2° ± 3°; 6% increase; \( p = 0.035 \)) groups post-intervention, with no change found in the landing or control groups. Passive plantar-flexor stiffness did not change in any group post-intervention. If the aim of a training program is to increase DROM, long-term static stretch training remains the
most effective method and may be necessary as an addition to task-specific training for athletes whose sports involve dynamic landings. Further research, however, should investigate the effects of these training interventions on landing performance, as well as their efficacy in reducing ankle and plantar-flexor muscle-tendon injury rates.

INTRODUCTION

Evidence suggests that a decreased dorsiflexion range of motion (ROM) is associated with increased ankle and plantar-flexor muscle-tendon unit (MTU) injury risk during sports involving landings\(^1\)-\(^3\), as well as biomechanical disadvantages during different tasks and in different cohorts\(^4\)-\(^6\). Training programs designed to increase dorsiflexion ROM may therefore improve landing biomechanics and, in turn, decrease injury risk although the optimal and most efficient type of training to achieve such adaptation in athletes engaged in landing sports is yet to be established.

Previous research involving training programs that influence joint ROM have included stretching, eccentric strength and task-specific training\(^7\)-\(^12\). Long-term stretch training studies have established that as long as a sufficient duration and frequency of stretching is performed, ROM will be increased\(^7\), \(^8\), \(^10\), \(^13\). Some stretch training studies have also found a concomitant decrease in passive resistive torque or passive MTU stiffness\(^10\), \(^11\). Other researchers, however, have found that stretch training did not significantly affect MTU stiffness\(^7\), \(^9\). Therefore, although stretch training programs are known to increase joint ROM, there is some contention regarding their effect on measures of MTU compliance such as passive resistive torque or passive stiffness.

Eccentric strength training has also been shown to increase joint ROM\(^8\), \(^12\) and may increase MTU compliance or decrease MTU stiffness\(^12\). Most research concerning the effects of eccentric strength training on MTU ROM, however, has been limited to
computer modelling or animal studies, which suggest that MTU length and ROM adaptations may be due to muscular remodelling, primarily through an increase in the number of sarcomeres in series within a muscle fibre. Human adaptations to bouts of eccentric exercise have typically been assessed non-invasively, with some studies associating increases in ROM with a shift in active muscle length-tension curves. However, the physiological mechanisms behind human adaptation to eccentric strength training programs in terms of MTU length, compliance or stiffness changes are not well understood.

Drop landing movements involve a rapid elongation (ballistic stretch) of the plantar-flexor MTU, with an eccentric contraction. It is reasonable to speculate, therefore, that task-specific training involving repeated bouts of drop landings may provide the necessary stretch and eccentric strength stimuli to affect both dorsiflexion ROM and stiffness, without the need to perform additional modes of exercise during training. Task-specific training studies involving running, hopping and drop jumping movements have assessed ankle ROM and MTU stiffness adaptations, although these active stimulus programs have involved movements that contained both eccentric and concentric muscle actions. McNair and Stanley compared the effects of running training, stretch training and a combination of both running and stretch training on dorsiflexion ROM and passive stiffness. Stretch training alone significantly increased dorsiflexion ROM and non-significantly increased passive stiffness, whereas running training alone significantly decreased passive stiffness without changing dorsiflexion ROM. The combined training protocol, however, produced the largest increase in ROM, with a non-significant decrease in passive stiffness. In another study, Kubo et al. demonstrated that hopping and drop jump training (concentric and eccentric contractions) on a sledge apparatus produced a significant increase in active ankle joint
stiffness without increasing active Achilles tendon stiffness. Therefore, depending on the task trained, MTU adaptations appear to be variable. However, no research has investigated the effects of task-specific training that involves eccentric muscle actions, without a concentric muscle contraction phase, on dorsiflexion ROM and plantar-flexor stiffness. Therefore, the purpose of this study was to determine whether a task-specific drop landing training program would have the same effect on dorsiflexion ROM and passive plantar-flexor stiffness as isolated stretching or eccentric strength training. We hypothesised that static stretch, eccentric strength and landing-specific training programs would all increase dorsiflexion ROM and decrease passive plantar-flexor stiffness, irrespective of any changes in eccentric plantar-flexor strength.

METHODS

Participants and study design

Ethical clearance was obtained from the University of Wollongong Human Research Ethics Committee (HE06/333) to conduct a parallel-design randomised controlled trial (RCT), with the study protocol adhering to the CONSORT guidelines\(^{18}\) (Fig. 11). Fifty five males were recruited via advertisements within the university campus, with 48 volunteers meeting the inclusion criteria of being male, less than 40 years of age and currently engaged in regular sport activity. Prior to participating, each recruit completed a ‘Physical Activity Readiness Questionnaire’\(^{19}\), a separate injury history questionnaire and provided written informed consent. Exclusion criteria included current training that closely resembled any of the study training protocols, specific plantar-flexor muscle training or current/previous injuries deemed to be contraindicated for completing the experimental protocol. All trial assessments and
Interventions were conducted within the Biomechanics Research Laboratory at the University of Wollongong.

![Flowchart Diagram]

**Figure 11:** Schematic diagram demonstrating overall experimental design, investigator and participant blinding and the flow of participants from enrolment through to follow-up assessment and analysis.

Assessment of calf MTU characteristics involved measuring the test limb only, which was determined by asking each participant to perform a single limb drop landing from a height of 32 cm on to their preferred landing foot. Following the baseline assessment of calf MTU function, participants were randomly assigned to one of four
groups: static stretch training, eccentric strength training, landing training or a control group for a 6-week intervention (Fig. 11). An independent researcher, blinded to testing and training, completed all randomisation procedures using a random numbers generator (http://www.randomizer.org/form.htm). Three participants in the experimental groups failed to complete a sufficient number of sessions in their respective training programs to meet the inclusion criteria for post-intervention assessment (>85%)\textsuperscript{20}, leaving a cohort of 45 participants (mean age = 22.4 ± 4.7 years; height = 180.5 ± 7.2 cm; mass = 74.5 ± 10.2 kg) for the final ‘per-protocol’ analysis\textsuperscript{21} of training effects (Fig. 11). The training intervention compliance rates for participants in the experimental groups are shown in Table 4. There were no significant differences between any of the intervention groups for participant height, body mass or age (Tab. 4).

Table 4: Mean (± SD) data and compliance rates for participants in the experimental training and control groups.

<table>
<thead>
<tr>
<th>Group</th>
<th>Number</th>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Mass (kg)</th>
<th>Goal sessions</th>
<th>Actual sessions</th>
<th>Compliance rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stretch</td>
<td>10</td>
<td>21.4 (5.1)</td>
<td>183.7 (7.2)</td>
<td>76.4 (9.1)</td>
<td>30</td>
<td>29.8 (0.6)</td>
<td>99.4 (2.0)</td>
</tr>
<tr>
<td>Strength</td>
<td>12</td>
<td>21.9 (4.0)</td>
<td>177.6 (5.2)</td>
<td>72.9 (8.4)</td>
<td>18</td>
<td>17.0 (0.9)</td>
<td>94.4 (4.7)</td>
</tr>
<tr>
<td>Landing</td>
<td>11</td>
<td>21.8 (3.0)</td>
<td>182.3 (6.9)</td>
<td>71.9 (13.0)</td>
<td>18</td>
<td>17.2 (0.6)</td>
<td>95.5 (3.4)</td>
</tr>
<tr>
<td>Control</td>
<td>12</td>
<td>24.2 (6.2)</td>
<td>179.1 (8.5)</td>
<td>76.8 (10.3)</td>
<td>--</td>
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<td>--</td>
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</tbody>
</table>

Baseline outcome measures of MTU ROM and stiffness were performed by the chief investigator [JWW], who was blinded to group allocation. Post-intervention assessments were performed by the same trained investigator; however, they were not blinded to group allocation. Bias was minimised by the presence of a blinded test assistant at each session to record the data using anonymous participant codes, as well as a strict objective measurement protocol. All participant codes were subsequently re-
Chapter 5

coded and randomised by an independent research assistant, so that all data analysis was then completed blind. Although it was not possible to blind participants to group training allocation, each participant was blinded to the other group interventions (Fig. 11).

Training interventions

All participants in the control group were asked to maintain current activity levels and to complete a daily activity diary that was collected and analysed each week by the investigators. The control group were also asked to refrain from commencing any new lower limb training while enrolled in the study.

Participants in the static stretch training group performed a stretch training protocol previously shown to be effective in increasing passive dorsiflexion ROM and decreasing passive stiffness\textsuperscript{10}. Four separate static weight-bearing stretches of the plantar-flexor MTU (knee flexed and knee extended, test and non-test limbs; Fig. 12) were performed five times per leg and held for 30 s each session\textsuperscript{13} for 5 days per week for 6 weeks. This resulted in a total training stimulus of 600 repetitions per leg and a training duration of approximately 30 minutes per session.

Figure 12: Demonstration of the four static stretch poses used during training.
Participants in the eccentric strength training group performed isokinetic eccentric exercises involving the plantar-flexor muscles of both legs at 30°.s⁻¹ and 180°.s⁻¹ on a KinCom dynamometer (Kinetic Communicator, Chattanooga Corp., Chattanooga, TN) 3 days per week for 6 weeks. These angular velocities were chosen as they have previously been associated with peak isokinetic plantar-flexor strength and power, respectively. Repetitions were performed in a non-weight-bearing position as described for the baseline measurement, as well as in a seated position on the KinCom dynamometer bench, with the participants’ hip and knee joints in 90° of flexion. Exercise progression was standardised, with a total of 3 sets of 6 repetitions per leg performed in Week 1 of the program, increasing to 6 sets of 8 repetitions per leg in Week 6, resulting in a total training stimulus of 590 repetitions per leg. Each participant was encouraged to give a maximal effort on all repetitions, repeated continuously within each set, with a 2-3 minute rest between sets. Total training time per session, minus the time taken by investigators to alter the equipment configuration between the different exercise modes, approximated 30 minutes. Furthermore, all exercises were performed to the end of each participant’s dorsiflexion ROM, which was determined at the start of each training session when the participant was in position on the KinCom dynamometer.

Participants in the drop landing training group performed a training protocol designed to utilise the notion of specificity, which included both single and double limb landings from a custom-built set of stairs (Fig. 13). The stairs were designed and constructed by a licensed carpenter and complied with Australian building codes (Ordinance 70, the Building Regulations of NSW) to provide a comfortable ascent to the starting drop height before each repetition, thereby minimising fatigue. Participants
rested for 2-3 minutes between sets and total training time was approximately 30 minutes per session.

Landing training was performed 3 days per week for 6 weeks, with all training progressions standardised. Due to the nature of this training, it began with a low number of repetitions and sets in Week 1, with training volumes reduced as exercise intensity (drop height) increased towards Week 6\(^{24}\). In Week 1, participants performed 2 sets of 10 repetitions of single-limb landings for each limb from a height of 48 cm, progressing to 20 repetitions per set by the end of Week 3. In Week 6 this progressed to a height of 72 cm and 8 repetitions. Double-limb landings were also performed by the drop landing training group. This progressed from 2 sets of 10 repetitions from a height of 72 cm in Week 1 to 20 repetitions per set by the end of Week 3, and then 2 sets of 8 repetitions from a height of 128 cm in Week 6, with a total training stimulus of 978 repetitions per leg. All participants in the landing training group were given verbal instructions and feedback to land comfortably and softly, by plantar-flexing their feet to contact the ground with their toes and ‘balls of feet’ first, and by bending their ankles and knees to absorb the landing.

\[\text{Figure 13: An example of a participant performing landing training from the maximum single limb landing height (72 cm) in Week 6 of the training intervention.}\]
Assessments of dorsiflexion ROM, plantar-flexor stiffness and eccentric strength

Passive dorsiflexion ROM (DROM) was measured using a weight-bearing standing lunge test previously established to have high reliability (ICC > 0.97)\(^6\). The standing lunge test was performed four times in two positions on the test limb (knee flexed and extended), with the foot and ankle position standardised for eversion/inversion and adduction/abduction. Using a Golllehon extendable goniometer (Model 01135; Lafayette Instrument Co., USA), the smallest ankle flexion angle from each position was subtracted from 90° to give the actual value for maximum weight-bearing DROM capacity\(^6\).

Passive plantar-flexor stiffness was measured using the KinCom dynamometer, with participants in a prone position on the dynamometer bench, with their foot firmly strapped to the foot-plate. The lateral malleolus was aligned with the axis of rotation of the dynamometer head and the knee was positioned in a statically flexed position (10°), thereby taking the gastrocnemius muscle off full stretch. The ankle was rotated from 5° of plantar-flexion to their pre-determined stretch limit, with participants instructed to relax their calf muscles and not actively resist the movement. The foot-plate was rotated slowly, at a constant velocity of 5°.s\(^{-1}\), in order to prevent muscular activation from stretch reflexes\(^{11, 25}\). This was verified by electromyography (EMG) data, sampled from four shank muscles and synchronised with the KinCom output data using MyoResearch XP collection software (Version 1.04.02, Noraxon Inc, Scottsdale, AZ). Any trials that involved visible muscle activation during dorsiflexion were excluded from further analysis. The passive calf MTU stiffness values were then determined by measuring the slope of the torque-angle curve generated between 15° and 20° of dorsiflexion, replicating similar methods used previously\(^7, 11, 25\). The analog data pertaining to the angular position, angular velocity and torque were sampled at 100 Hz directly from the
KinCom PC via a National Instruments DAQpad 6015/1016 using the same MyoResearch collection software.

Isokinetic plantar-flexor strength was measured eccentrically (30°.s\(^{-1}\) and 180°.s\(^{-1}\)) while participants were in the same prone position on the KinCom dynamometer. During the eccentric measures, the test limb for each participant was rotated from near maximal plantar-flexion into near maximal dorsiflexion (5° less than peak passive dynamometer dorsiflexion ROM). Participants performed a sub-maximal warm-up and familiarisation set at the test velocities in each exercise mode with a 3 minute rest period after each set. The maximal eccentric plantar-flexor strength tests (30°.s\(^{-1}\) and 180°.s\(^{-1}\)) were assigned randomly and involved a sub-maximal repetition followed by three maximal efforts, whereby participants were given strong verbal encouragement to push maximally. Analog data were sampled in the same manner as data from the passive stiffness test and the peak strength values were obtained from the largest peak in the angle-tension curves generated for each isokinetic test.

**Statistical analyses**

All data sets were tested for normality using the Kolmogorov-Smirnov statistic with a Lilliefors significance correction. A two-way ANOVA (assessment day x training group) model was then used to determine the effects of training on calf MTU characteristics. Where main effects or interactions were found to be significant, *post hoc* tests (*t*-tests) were conducted to determine whether there were any significant differences (training effects) between pre- and post-intervention assessments for each training group. An alpha level was set at 0.05 for all statistical analyses and all data were analysed using SPSS for Windows (v. 17, SPSS Inc., Chicago, IL) and were expressed as mean (± SD) throughout.
RESULTS

The two-way ANOVA revealed a significant effect of assessment day and significant group x day interactions for DROM in both the knee flexed \((p = 0.002; p = 0.001)\) and knee extended \((p = 0.007; p < 0.001)\) positions. Post hoc analyses revealed a significant increase in DROM for the stretch and eccentric strength training groups when comparing pre- to post-intervention assessment results (Tab. 5). However, there were no significant main effects or significant group x day interactions for passive MTU stiffness. For eccentric strength at \(30^\circ.s^{-1}\), there was a significant group x day interaction \((p = 0.001)\) and significant main effects of both training group \((p = 0.012)\) and assessment day \((p < 0.001)\). Post hoc analyses revealed that the control and strength training groups made significant increases in peak eccentric strength \((30^\circ.s^{-1})\) whereby the percentage changes in peak eccentric strength for the control, stretch, eccentric strength and drop landing training groups were +14\%, +19\%, +51\% and +12\%, respectively. For eccentric strength at \(180^\circ.s^{-1}\), a non-significant, albeit notable interaction \((p = 0.064)\) and a significant main effect for day \((p < 0.001)\) was found. Post hoc analyses showed that the control, strength training and drop landing training groups each significantly increased eccentric strength at \(180^\circ.s^{-1}\) whereby the percentage changes in peak eccentric strength for the control, stretch, eccentric strength and drop landing training groups were +7\%, +10\%, +25\% and +12\%, respectively.

DISCUSSION

Our hypothesis that all training methods would increase DROM was partially supported by the results of this RCT whereby the stretch and eccentric strength training groups both significantly increased DROM post-intervention, in both the knees flexed and extended positions. This finding of increased DROM following stretch and strength...
Table 5: Mean (± SD) values for the calf muscle flexibility and strength measures. Data represent the values for baseline and post-intervention and the mean changes resulting from the training intervention for each group (NB: a neutral foot-shank alignment = 0°; all positive angles denote dorsiflexion).

<table>
<thead>
<tr>
<th>Training Group</th>
<th>Control ( n = 12 )</th>
<th>Stretch ( n = 10 )</th>
<th>Strength ( n = 12 )</th>
<th>Landing ( n = 11 )</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Weight-bearing DROM (knee flexed; °)</strong> *, #</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>44.3 (6.3)</td>
<td>44.3 (3.8)</td>
<td>40.5 (4.1)</td>
<td>43.4 (5.1)</td>
</tr>
<tr>
<td>Post-intervention 2, 3</td>
<td>43.0 (6.0)</td>
<td>47.4 (3.4)</td>
<td>42.4 (4.5)</td>
<td>44.3 (5.7)</td>
</tr>
<tr>
<td><strong>Weight-bearing DROM (knee extended; °)</strong> *</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>40.7 (5.2)</td>
<td>39.3 (4.9)</td>
<td>38.0 (4.5)</td>
<td>41.8 (5.2)</td>
</tr>
<tr>
<td>Post-intervention 2, 3</td>
<td>39.3 (4.6)</td>
<td>45.0 (4.2)</td>
<td>40.3 (4.9)</td>
<td>41.6 (5.7)</td>
</tr>
<tr>
<td><strong>Passive stiffness (Nm.°⁻¹)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>1.25 (0.38)</td>
<td>1.57 (0.49)</td>
<td>1.72 (0.68)</td>
<td>1.56 (0.60)</td>
</tr>
<tr>
<td>Post-intervention</td>
<td>1.41 (0.41)</td>
<td>1.81 (0.68)</td>
<td>1.62 (0.56)</td>
<td>1.52 (0.34)</td>
</tr>
<tr>
<td><strong>Peak eccentric strength (30°.s⁻¹; Nm.kg⁻¹)</strong> * * *, #</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>2.19 (0.60)</td>
<td>2.57 (0.90)</td>
<td>2.52 (0.66)</td>
<td>2.55 (0.26)</td>
</tr>
<tr>
<td>Post-intervention 1, 3</td>
<td>2.49 (0.55)</td>
<td>3.08 (0.91)</td>
<td>3.81 (0.72)</td>
<td>2.85 (0.38)</td>
</tr>
<tr>
<td><strong>Peak eccentric strength (180°.s⁻¹; Nm.kg⁻¹)</strong> *</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Baseline</td>
<td>2.52 (0.34)</td>
<td>2.71 (0.68)</td>
<td>2.76 (0.60)</td>
<td>2.60 (0.35)</td>
</tr>
<tr>
<td>Post-intervention 1, 3, 4</td>
<td>2.69 (0.39)</td>
<td>2.98 (0.84)</td>
<td>3.44 (0.68)</td>
<td>2.90 (0.36)</td>
</tr>
</tbody>
</table>

Two-way ANOVA (assessment day x training group):
* = significant main effect of assessment day; ** = significant main effect of training group; # = significant interaction.

Post hoc t-tests (significant difference between baseline and post-intervention assessments):
1 = Control group; 2 = Stretch group; 3 = Strength group; 4 = Landing group.

Training was consistent with previous research\(^{10,12,16,26}\). In contrast to our hypothesis, however, task-specific landing training did not significantly increase DROM. As landing can be considered an active and ballistic stretch stimulus, our results are also in contrast to the results of Mahieu et al.\(^{26}\) and Woolstenhulme et al.\(^{27}\), who found ballistic stretching programs that involved ‘bouncing’ while at end ROM, increased flexibility as measured by a test of DROM and the ‘sit and reach’ test. We speculate that the rapid ballistic-type stretch provided by the landing training protocol in the present study elongated the plantar-flexor MTU well within each participant’s DROM and, therefore, did not cause strain at the end of the physiological range of the MTU. Previous research has demonstrated that ankle dorsiflexion ROM during drop landings tends to peak at
less than $30^\circ$ and consequently, the landing group, with a mean DROM of more than $40^\circ$ pre-intervention, may not have received a sufficient stretch stimulus, particularly at end ROM, to induce change. Task-specific landing training may therefore require the end of MTU ROM to be reached for ROM increases to be achieved, although this notion requires further investigation.

Research suggests that joint ROM increases through eccentrically-induced MTU damage require maximal efforts through to end ROM$^{28, 29}$. Although the stretch and strength training groups both significantly increased DROM, the magnitude of the increase in range in the stretch group (knee flexed $3^\circ$, 7%; knee extended $6^\circ$, 15%), consistent with previous research$^{10}$, was clearly greater than that of the eccentric strength training group (knee flexed $2^\circ$, 5%; knee extended $2^\circ$, 6%). It is also acknowledged that the DROM changes made by the strength training group may not be beyond the range of measurement error in the present study and may not necessarily reflect functional adaptation. The magnitude of the DROM increase achieved through eccentric strength training was also less than that achieved by Mahieu et al.$^{12}$ (knee flexed $6^\circ$, 13%; knees extended $6^\circ$, 23%) and may be attributed to differences in the training protocols. The protocol investigated by Mahieu et al.$^{12}$ involved participants in weight-bearing postures performing slow and controlled heel drop movements, ensuring the participants moved to their end dorsiflexion ROM. The non-weight-bearing position used in the current study on the KinCom, with the foot-strap and dynamometer-pedal configuration, caused some heel lift during training which, although not quantified, did prove difficult to control, and may have provided a limitation that decreased the stretch stimulus by reducing the end dorsiflexion ROM.

Although the eccentric strength protocol was aimed at increasing DROM, as expected, eccentric strength training did result in increased peak eccentric strength
values at both assessment velocities. It must be noted; however, that no familiarisation or practice session was conducted for the strength testing protocols and, as a result, a learning effect was evidenced by concurrent increases in strength for the control and other experimental groups at each eccentric angular velocity. However, the magnitude of the increase in strength was substantially greater for the strength-specific group at 30°.s\(^{-1}\) (51% versus 12% - 19% for the other three groups), indicating that the strength group were exposed to a training stimulus sufficient for an adaptive response. Nonetheless, although there were greater strength adaptations evident for the strength training group, torque output during eccentric training was not monitored, limiting any conclusions regarding the maximal nature of training efforts.

Our hypothesis that training would significantly decrease passive plantar-flexor stiffness was not supported by our results obtained for any of the training interventions in the present study. Although this finding is in contrast with previous research that has reported a decrease in passive MTU resistance with stretch, eccentric strength and running training\(^9\text{--}^{12}\), it is consistent with other research of stretch, strength and task-specific hopping and drop jump training\(^7\text{,}^9\text{,}^{17}\). The lack of change in passive stiffness in the current study may suggest that the increase in DROM found in the stretch and eccentric strength training groups could be attributed to an increased tolerance to stretch pain. However, the magnitude of the increase in DROM for the stretch group resembles results found by other researchers who were able to show that ROM changes from an almost identical protocol were attributable to MTU viscoelastic change\(^10\). Therefore, although researchers continue to debate the benefits of acute bouts of pre-exercise stretching for enhancing performance or reducing injury risk\(^30\), the results of this study support the literature regarding the effects of long-term stretching. That is, we were able to demonstrate that long-term stretch training was an effective way of substantially
increasing DROM, without affecting passive plantar-flexor stiffness, while eccentric strength training proved to have little effect on DROM and task-specific training was ineffective at changing DROM at all.

CONCLUSIONS

Stretch and eccentric strength training of the plantar-flexor MTU were found to significantly increase DROM, although stretch training may be the most effective method for making functional adaptation at the ankle joint. Although the task-specific landing training program was designed to provide a ballistic stretch and eccentric stimulus to the plantar-flexor MTU, no significant change in DROM was observed in this group. Passive plantar-flexor stiffness was unaffected by any of the training protocols and was also unchanged in the control group post-intervention. Therefore, if the aim of a training program is to increase DROM, then long-term static stretch training is the most useful, without necessarily altering MTU compliance. Further research, however, should investigate the effects of these training interventions on the performance of tasks such as landings, as well as their efficacy in reducing ankle and plantar-flexor MTU injury rates.

REFERENCES


27. Woolstenhulme MT, Griffiths CM, Woolstenhulme EM, & Parcell AC. Ballistic stretching increases flexibility and acute vertical jump height when combined with


Chapter 6

Effects of plantar-flexor strength and flexibility training on ankle mechanics during drop landings: A randomised controlled trial

This chapter is an amended version of the manuscript: Whitting JW, Steele JR, McGhee DE and Munro BJ. Effects of plantar-flexor strength and flexibility training on ankle mechanics during drop landings: A randomised controlled trial. Clinical Biomechanics. Submitted for publication December, 2010.

ABSTRACT

The purpose of this study was to determine the effects of static stretch training, eccentric strength training and task-specific drop landing training on ankle biomechanics during drop landings. Muscular activity, three-dimensional kinematics and joint kinetics were assessed during drop landings performed by 45 male volunteers before and after a 6-week training intervention, using a parallel-design assessor-blinded randomised trial. The three experimental training groups included static stretch (n = 10), eccentric strength (n = 12) and drop landing training (n = 11); and one control group (n = 12). Post-intervention, participants in the drop landing training group displayed earlier peak activity of the lateral gastrocnemius muscle (-59 ± 135 ms; group-day interaction: \( p = 0.014 \)), were significantly more plantar flexed at initial foot-ground contact (~4°; group-day interaction: \( p = 0.032 \)) and took more time to dissipate landing loads relative to participants in the other training groups. This was in contrast to the other training groups where landing time decreased (group-day interaction; \( p = 0.040 \)). The stretch group displayed significantly less peak dorsiflexion during the drop landing task, while the landing biomechanics of the control and eccentric strength training groups did not significantly change post-intervention. Landing-specific training may be beneficial for
injury prevention for athletes involved in landing sports by improving their muscular coordination and increasing load absorption time, whereas stretch training, designed to increase DROM, may reduce plantar-flexor MTU strain, without causing substantial changes to landing technique.

INTRODUCTION

During landing movements, downward momentum of the body is arrested by flexing the joints of the lower limb following foot-ground contact, with the ankle being the first major joint beyond the foot to absorb the ground reaction forces\textsuperscript{1,2}. The overall landing strategy and the magnitude of the loads imposed upon the more proximal joints is moderated by the ankle as the plantar-flexor muscles eccentrically control dorsiflexion, creating an internal plantar-flexion moment that transmits force through the plantar-flexor muscle-tendon unit (MTU)\textsuperscript{1-3}. Increasing joint range of motion (ROM) during a landing task may increase the amount of time taken to absorb the impact, thereby decreasing the ground reaction forces and joint loading\textsuperscript{4,5}. It may be postulated, therefore, that reduced dorsiflexion capacity, may compromise the ability of an individual to control a landing movement or increase the strain imposed upon the passive and active structures of the plantar-flexor muscles while they are being lengthened. This may account for retrospective research findings that have demonstrated an association between decreased passive dorsiflexion ROM and sport-related injuries to the ankle, Achilles tendon and plantar-flexor muscles, particularly during landing sports\textsuperscript{6-8}.

To date, however, there is only sparse biomechanical evidence indicating that limited dorsiflexion ROM impairs function or increases loading during dynamic tasks. Reduced dorsiflexion ROM in the elderly has been negatively correlated with sit-to-
stand and walking tasks\textsuperscript{9}. Furthermore, young adult males with reduced dorsiflexion ROM have been shown to use less ankle ROM during stair descents, increasing ankle moments\textsuperscript{10}, and physically active young adult males with reduced weight-bearing dorsiflexion ROM have been shown to perform a drop landing with their plantar-flexor MTU in a more lengthened state, which was speculated to increase their risk of MTU strain injury\textsuperscript{11}. The results of these studies suggest that reduced dorsiflexion ROM may place individuals at a biomechanical disadvantage in terms of both function and loading during weight-bearing tasks. It may be speculated, therefore, that training programs designed to increase dorsiflexion ROM, including static stretching\textsuperscript{12} or eccentric strength training\textsuperscript{13}, may improve the biomechanics of landings, thereby decreasing injury risk. However, the effects of static plantar-flexor MTU stretch training on the ability of an individual to perform a drop landing movement, particularly with a focus on injury prevention implications and not performance enhancements, has not been investigated. Similarly, although it is widely accepted that strength training modalities should try to specifically replicate the task trained in terms of muscle action, ROM and velocity\textsuperscript{14}, the effects of eccentric strength training on the biomechanical performance of an eccentric landing task are yet to be explored.

Task-specific training studies have demonstrated small effects on musculotendinous adaptations of the plantar-flexor MTU. Running training has been found to increase dorsiflexion ROM\textsuperscript{15}, and hopping and drop jumping training have altered plantar-flexor stiffness\textsuperscript{16}. Drop landing training is yet to be investigated in relation to plantar-flexor adaptation or in relation to improving the biomechanics of a drop landing movement for injury prevention, despite the specific application of such training to drop landing technique. Therefore, the purpose of this exploratory investigation was to determine the effects of static stretch training, eccentric strength
training and task-specific drop landing training on ankle biomechanics during a drop landing task. We hypothesised that stretch training and eccentric strength training, each designed to increase dorsiflexion capacity, as well as task-specific drop landing training would increase muscular coordination and decrease the ground reaction forces, plantar-flexor moment and Achilles tendon force generated during landing by increasing load absorption time.

METHODS

Participants and study design

Ethical clearance was obtained from the University of Wollongong Human Research Ethics Committee (HE06/333) to conduct a parallel-design randomised controlled trial (RCT), with the study protocol adhering to the CONSORT guidelines (see Fig. 11, Chapter 5). Fifty five volunteers were recruited via advertisements within the university campus, with 48 meeting the inclusion criteria of being male, less than 40 years of age and currently engaged in regular sport activity. Prior to participating, each recruit completed a ‘Physical Activity Readiness Questionnaire’, a separate injury history questionnaire and a written informed consent form. Exclusion criteria was current training that closely resembled any of the study training protocols, specific plantar-flexor muscle training, or current or previous injuries deemed to be contraindicated for completing the experimental protocol. All landing assessments and training interventions were conducted within the Biomechanics Research Laboratory at the University of Wollongong.

Assessments of drop landing technique involved measuring the participant’s test limb only, which was determined by asking each participant to perform a single limb drop landing from a height of 32 cm onto their preferred landing foot. Following
baseline assessment of drop landing technique, participants were randomly assigned to one of four groups: (i) static plantar-flexor stretch training; (ii) eccentric strength training of the plantar-flexor MTU, (iii) landing specific training or (iv) a control group, with the training groups undergoing a 6-week intervention (Fig. 11). An independent researcher, blinded to testing and training, completed all randomisation procedures using a random numbers generator (http://www.randomizer.org/form.htm). Three participants in the experimental groups failed to complete a sufficient number of sessions in their respective training programs to meet the inclusion criteria for post-intervention assessment (>85%)\(^{19}\), leaving a cohort of 45 participants (mean age = 22.4 ± 4.7 years; height = 180.5 ± 7.2 cm; mass = 74.5 ± 10.2 kg) for the final ‘per-protocol’ analysis\(^{20}\) of the training effects (Fig. 11). The training session compliance rates for participants in the experimental groups were 99.4% ± 2.0%, 94.4% ± 4.7% and 95.5% ± 3.4% for the stretch, eccentric strength and drop landing training groups, respectively. There was no significant difference between any of the intervention groups for participant height, body mass or age.

The collection of baseline data pertaining to drop landing technique was performed by investigators who were blinded to group allocation. Post-intervention data collection was performed by the same investigators; however they were not blinded to group allocation. Bias was minimised during the post-intervention data collection sessions by the presence of a research assistant who was blinded to the training interventions and who recorded the data using anonymous participant codes and the use of objective data collection methods. All participant codes were subsequently re-coded and randomised by another independent research assistant, enabling all data analysis to be completed blind. Although it was not possible to blind participants to group training allocation, each participant was blinded to the other group interventions (Fig. 11).
Training interventions

All participants in the control group (n = 12; mean height = 179.1 ± 8.5 cm, mean body mass = 76.8 ± 10.3 kg and mean age = 24.2 ± 6.2 years) were asked to maintain current activity levels, and completed a daily physical activity diary that was collected and analysed each week by the investigators, confirming that no participant in the control group commenced any new lower limb training while enrolled in the study.

Participants in the static stretch training group (n = 10; mean height = 183.7 ± 7.2 cm, mean body mass = 76.4 ± 9.1 kg and mean age = 21.4 ± 5.1 years) performed a stretch training protocol previously shown to be effective in increasing passive DROM12. Four separate static weight-bearing stretches of the plantar-flexor MTU (knee flexed and knee extended, test and non-test limbs) were performed five times per leg and held for 30 s each session21 for 5 days per week for 6 weeks. This resulted in a total training stimulus of 600 repetitions per leg and a training duration of approximately 30 minutes per session.

Participants in the eccentric strength training group (n = 12; mean height = 177.6 ± 5.2 cm, mean body mass = 72.9 ± 8.4 kg and mean age = 21.9 ± 4.0 years) performed isokinetic eccentric exercises of the plantar-flexor muscles of both legs at 30°.s⁻¹ and 180°.s⁻¹ on a KinCom dynamometer (Kinetic Communicator, Chattecx Corp., Chattanooga, TN) 3 days per week for 6 weeks. These angular velocities were chosen as they have previously been associated with peak isokinetic plantar-flexor strength and power, respectively22, thereby providing maximal stimuli. Repetitions were performed in a non-weight-bearing position as described for the baseline measurement, as well as in a seated position on the KinCom dynamometer bench, with the participants’ hip and knee joints in 90° of flexion. Exercise progression was standardised, with a total of 3 sets of 6 repetitions per leg performed in Week 1 of the program, increasing to 6 sets of
8 repetitions per leg in Week 6, resulting in a total training stimulus of 590 repetitions per leg. Each participant was encouraged to give a maximal effort on all repetitions, repeated continuously within each set, with a 2 to 3 minute rest between sets. Total training time per session, minus the time taken by investigators to alter the equipment configuration between the different exercise modes, approximated 30 minutes. All exercises were performed to the end of each participant’s dorsiflexion ROM\textsuperscript{13,23}, which was determined in position on the KinCom dynamometer at the start of each training session.

Participants in the drop landing training group (n = 11; mean height = 182.3 ± 6.9 cm, mean body mass = 71.9 ± 13.0 kg and mean age = 21.8 ± 3.0 years) performed a training protocol designed to utilise the notion of specificity\textsuperscript{14}, which included both single and double limb landings from a custom-built set of stairs. The stairs were designed and constructed by a licensed carpenter and complied with Australian building codes (Ordinance 70, the Building Regulations of NSW) to provide a comfortable ascent to the starting drop height before each repetition, thereby minimising fatigue. Participants rested for 2-3 minutes between sets and total training time was approximately 30 minutes per session.

Drop landing training was performed 3 days per week for 6 weeks, with all training progressions standardised. Due to the nature of this training, it began with a low number of repetitions and sets in Week 1, with training volumes reduced as exercise intensity (drop height) increased towards Week 6\textsuperscript{24}. In Week 1, participants performed 2 sets of 10 repetitions of single-limb landings for each limb from a height of 48 cm, progressing to 20 repetitions per set by the end of Week 3. In Week 6 this progressed to a height of 72 cm, with eight repetitions per set. Double-limb landings were also performed by the drop landing training group. This progressed from 2 sets of 10
repetitions from a height of 72 cm in Week 1 to 20 repetitions per set by the end of Week 3, and then 2 sets of 8 repetitions from a height of 128 cm in Week 6, with a total training stimulus of 978 repetitions per leg. All participants in the landing training group were given verbal instructions and feedback to land comfortably and softly, by plantar-flexing their feet to contact the ground with their toes and ‘balls of feet’ first, and by bending their ankles and knees to absorb the landing.

**Drop landing technique assessment**

Participants performed a series of single limb drop landings from a height of 72 cm\(^{11}\), resulting in a vertical descent velocity of \(3.21 \pm 0.17\) m.s\(^{-1}\). Participants were instructed to lead with their test landing limb and allow themselves to free-fall from the custom-designed staircase and land onto their test foot, thereby completing a controlled landing movement designed to strain the plantar-flexor MTU. A trial was deemed successful when a participant landed with their foot within the confines of the force platform and all participants were required to perform five successful trials.

EMG recordings were taken from four shank muscles (tibialis anterior (TA), soleus (SO), gastrocnemius medialis (MG) and gastrocnemius lateralis (LG)) using electrode placement sites recommended by Cram et al.\(^{25}\) and processed according to guidelines endorsed by the International Society of Electrophysiology and Kinesiology\(^{26}\). The raw EMG signals were passed through a fourth-order zero-phase-shift Butterworth filter (high-pass; frequency cut-off \((f_c) = 15\) Hz) and then full-wave rectified and filtered again using a fourth-order zero-phase-shift Butterworth low-pass filter \((f_c = 20\) Hz). The resulting EMG curves closely resembled the shape of the raw muscle tension curves, albeit providing a smoothed representation that also retained the original critical temporal characteristics\(^{27}\).
The timing of muscle burst onsets and peak amplitudes were determined from the smoothed linear envelopes representing each muscle burst that had its onset immediately prior to initial foot-ground contact (threshold = 8% peak amplitude)\(^{27}\). This was deemed to represent the activity corresponding with the initial impact absorption during the most critical phase of the landing, when the ankles of each participant were undergoing eccentrically controlled dorsiflexion. The validity of the placement of computer-generated markers was confirmed by visually inspecting each individual muscle’s raw and filtered EMG signals, thereby minimising processing errors\(^{28,29}\). The temporal variables calculated for each trial included muscle burst onsets and peak amplitudes, relative to initial foot-ground contact.

The ground reaction force data generated by each subject at initial foot-ground contact were recorded using a Kistler multichannel force platform (Type 9281B, Kistler Instrumente AG Winterthur, Switzerland; 600 mm x 400 mm; 1000 Hz). The top surface of the force platform was layered with EVA rubber (12 mm thickness) adhered to compressed timber (10 mm thickness) and securely bolted to the platform. Although cushioned landing surfaces may affect the magnitude of force data\(^{30}\), researchers have accepted this limitation as a necessary safety precaution when investigating landing forces of such magnitudes\(^{1,27}\). The eight analog ground reaction force channels were summed to obtain force-time curves in the three orthogonal planes for each individual trial and filtered using a fourth-order zero-phase-shift Butterworth low-pass filter (\(f_c = 100\) Hz). The peak vertical ground reaction force (VGRF) was calculated in Newtons (N) and then normalised for participant body weight (BW).

Kinematics of the foot and shank segments\(^{11}\) were assessed in three dimensions during each landing (200 Hz; Opto\(TRAK\) 3020, Northern Digital Inc., Waterloo, Canada) with dynamic infra-red markers placed on the 2\(^{nd}\) metatarsal distal head, 5\(^{th}\)
metatarsal distal head, 1<sup>st</sup> metatarsal proximal head, 5<sup>th</sup> metatarsal proximal head, lateral calcaneus, lateral malleolus, distal/posterior calcaneus, medial calcaneus, medial malleolus, mid anterior tibia, lateral femoral condyle, and medial femoral condyle. Static infra-red markers were placed on the 1<sup>st</sup> metatarsal distal head and the proximal/posterior calcaneus. All data were filtered (Butterworth, fourth-order low-pass zero-phase-shift) at 15 Hz following the results of a residual frequency analysis and dorsiflexion angular velocities, internal plantar-flexion moments, Achilles tendon forces (ATF) and eversion angles were calculated. Ankle joint kinetics and raw ground reaction force data were also filtered at the same rate (15 Hz; low-pass) and used as input into an inverse dynamics solution to minimise the possibility of impact peak errors<sup>31, 32</sup>. The ATF were calculated by dividing the internal plantar-flexion moment by the Achilles tendon moment arm using a regression equation developed by Self & Paine<sup>1</sup>. All moments were normalised to body mass and the ATF were normalised to each participant’s body weight. All signal processing and analysis was performed using Visual3D software (V3D; C-Motion, Inc., Germantown, MD; Version 4.00.15).

Statistical analyses

All data sets were tested for normality using the Kolmogorov-Smirnov statistic with a Lilliefors significance correction. A two-way ANOVA (assessment day x training group) model was then used to determine the effects of training on all outcome measures characterising ankle biomechanics during drop landings. Where main effects or interactions were found to be significant, post hoc tests (t-tests) were conducted to determine whether there were any significant differences (training effects) between pre- and post-intervention tests for each training group. An alpha level was set at 0.05 for all statistical analyses and all data were analysed using SPSS for Windows (v. 17, SPSS Inc., Chicago, IL) and were expressed as mean (± SD) throughout.
RESULTS

Muscle activity

A significant group x day interaction ($p = 0.014$; Fig. 14) was found for timing of the peak LG amplitude. Post hoc analysis indicated that the drop landing training group displayed earlier peak LG amplitude ($p = 0.056$), although this just failed to reach statistical significance. A significant main effect of assessment day was found on TA onset ($p = 0.004$), although this effect was moderated by training group whereby TA tended to be activated earlier for the drop landing training group as indicated by the group x day interaction approaching significance ($p = 0.076$, Tab. 6). Although non-significant ($p = 0.069$), the group x day interaction also indicated a trend for earlier LG onset in the drop landing trained participants relative to the other participant groups (Tab. 6).

![Figure 14: Significant group x day interaction ($p = 0.014$) for mean data pertaining to the peak EMG amplitude for lateral gastrocnemius during drop landings. Data represent the timing of activity relative to initial foot-ground contact (IC; 0 ms) for baseline and post-intervention assessments.](image)

Ground reaction forces and ankle joint kinematics and kinetics

Significant main effects of assessment day ($p = 0.025$) and training group ($p = 0.041$) and a significant group x day interaction on the temporal variable characterising landing absorption time (time to reach the peak dorsiflexion angle; $p = 0.040$), indicated
Table 6: Mean (± SD) values for temporal variables characterising the timing of muscle activation events relative to initial foot-ground contact. Data represent baseline and post-intervention values resulting from the training intervention for each group.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Training Group</th>
<th></th>
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<th></th>
</tr>
</thead>
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<tr>
<td></td>
<td>Control n = 12</td>
<td>Stretch n = 10</td>
<td>Strength n = 12</td>
<td>Landing n = 11</td>
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</tr>
<tr>
<td>Muscle burst onsets (ms)</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Tibialis anterior *</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Baseline</td>
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<tr>
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<tr>
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<tr>
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<tr>
<td>Tibialis anterior</td>
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<td></td>
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<td></td>
</tr>
<tr>
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<td>162 (78)</td>
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<tr>
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<td>127 (124)</td>
<td>140 (53)</td>
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<td>Soleus</td>
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<td>Baseline</td>
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<td>Post-intervention</td>
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<td></td>
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<tr>
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<td>44 (86)</td>
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</tr>
<tr>
<td>Post-intervention</td>
<td>62 (74)</td>
<td>28 (67)</td>
<td>43 (67)</td>
<td>-59 (135)</td>
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Two-way ANOVA (assessment day x training group): * = significant main effect of assessment day; ** = significant main effect of training group; # = significant day x group interaction.

Post hoc t-tests (significant difference between baseline and post-intervention assessments): † = Control group; ‡ = Stretch group

A longer landing absorption time was displayed by the drop landing training group relative to the other participant groups (Fig. 15, Tab. 7). However, there were no significant main effects or interactions for the ground reaction forces generated during landing (Tab. 7). There was a significant main effect of assessment day (p = 0.016) and a significant group x day interaction (p = 0.032; Fig. 16) for the plantar-flexion angles noted at initial foot-ground contact for each training group, with *post hoc t*-tests
revealing a significant increase in post-intervention values for plantar-flexion angle at initial foot-ground contact for the landing group ($p = 0.032$; Tab. 7). There was also a significant main effect of day on the peak eversion angles ($p = 0.020$), although there was no significant interaction for this variable. No significant main effects or interactions for any other kinematic or kinetic variable characterising the participants’ landing biomechanics were found, although the group x day interaction for the total ankle ROM during the landing movement from initial foot-ground contact to the peak dorsiflexion angle approached significance ($p = 0.051$). Post hoc analyses showed that total ankle ROM increased significantly post-intervention for the drop landing training group (Tab. 7).

**Figure 15:** Significant group x day interaction ($p = 0.040$) for mean data pertaining to the time to reach the peak dorsiflexion angle during drop landings. Data represent the timing of activity relative to initial foot-ground contact (0 ms) for baseline and post-intervention assessments for each training group.

**Figure 16:** Significant group x day interaction ($p = 0.032$) for mean data pertaining to the ankle plantar-flexion angle at initial foot-ground contact during drop landings. Data represent angles at baseline and post-intervention assessments for each training group.
Table 7: Mean (± SD) values for variables characterising ground reaction forces and ankle joint kinematics and kinetics during drop landings, for each training group. Data represent baseline and post-intervention values resulting from the training intervention for each group.

<table>
<thead>
<tr>
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<td>Control n = 12</td>
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<td>Ground reaction force</td>
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<td>Peak vertical GRF (N)</td>
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<td>Post-intervention</td>
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<td>Peak vertical GRF (BW)</td>
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<td>Post-intervention</td>
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<td>Time from IC to peak dorsiflexion angle (ms)</td>
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<tr>
<td>Baseline</td>
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<td>Post-intervention</td>
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<tr>
<td>Plantar-flexion angle at IC (°)</td>
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<td>Baseline</td>
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<td>Post-intervention</td>
<td>24.3 (6.1)</td>
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<tr>
<td>Peak dorsiflexion angle (°)</td>
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<tr>
<td>Baseline</td>
<td>27.0 (4.4)</td>
</tr>
<tr>
<td>Post-intervention</td>
<td>26.5 (5.7)</td>
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<tr>
<td>Total ankle ROM (°)</td>
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<tr>
<td>Baseline</td>
<td>51.5 (9.2)</td>
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<td>Post-intervention</td>
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<td>Peak dorsiflexion angular velocity (°.s(^{-1}))</td>
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<tr>
<td>Baseline</td>
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<td>Post-intervention</td>
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<tr>
<td>Peak eversion angle (°)</td>
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<td>Baseline</td>
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<tr>
<td>Post-intervention</td>
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<td>Eversion angle at peak ATF (°)</td>
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<tr>
<td>Baseline</td>
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<td>Post-intervention</td>
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<tr>
<td>Joint kinetics</td>
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<tr>
<td>Peak plantar-flexion moment (N.m.kg(^{-1}))</td>
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</tr>
<tr>
<td>Baseline</td>
<td>2.85 (0.33)</td>
</tr>
<tr>
<td>Post-intervention</td>
<td>3.51 (0.68)</td>
</tr>
</tbody>
</table>

GRF = ground reaction force; BW = body weights; IC = initial foot-ground contact; ATF = Achilles tendon force

Two-way ANOVA (assessment day x training group):
* = significant main effect of assessment day; # = significant day x group interaction.

Post hoc t-tests (significant difference between baseline and post-intervention assessments):
= Stretch group; = Landing group
Chapter 6

DISCUSSION

Strain type injuries to the Achilles tendon and plantar-flexor muscle bellies are considered to be a function of the magnitude of the applied force, the limits in available ROM and the length of the MTU when the strain occurs; or a combination of any of these factors\(^8,33,34\). In the present study, the stretch training group used significantly less dorsiflexion ROM during the landing movement post-intervention, although they had significantly more passive DROM available post-intervention (see Chapter 5), and displayed a tendency to decrease the peak ATF generated during landing (by an average \(\frac{1}{4}\) BW), post-intervention. Accordingly, the stretch trained participants likely experienced less strain to their plantar-flexor MTU and throughout a more comfortable range of the MTU following training. It should be noted, however, that stretch-trained participants also significantly reduced the time taken to reach their peak dorsiflexion angle during load absorption, and this may represent an adverse increase in the force loading rate.

With respect to the eccentric strength training group, there were no apparent changes to their biomechanical landing strategies in the present study, despite previously displaying the greatest percentage increase in peak eccentric strength of all the training groups and with a small but significant increase in DROM (see Chapter 5). While it is acknowledged that the eccentric strength training velocities (30°.s\(^{-1}\) and 180°.s\(^{-1}\)) may not have approximated the angular velocities characteristic of drop landings (>1000°.s\(^{-1}\)) closely enough to provide a functional strength adaptation, the small increase in DROM previously found in the eccentric strength group (see Chapter 5) may also not have been functionally relevant, particularly when compared with the stretch group.
The drop landing training group significantly altered their landing biomechanics in the present study, despite being shown previously to make no change to their passive DROM (see Chapter 5). In terms of neuromuscular adaptation in the present study, the drop landing training group had an earlier timing of peak LG activity, such that it coincided with peak MG activity. There was also a trend for earlier onset of LG and TA as indicated by close to significant group x day interactions for these variables (Tab. 6). Due to the injury propensity of MG during explosive running, jumping and landing movements\textsuperscript{33, 35}, the coordinated timing of peak LG and MG activity, with a tendency to coordinate muscular onsets earlier prior to initial foot-ground contact, may be favourable neuromuscular adaptations in terms of peak load absorption. It also provides support for the concept of specificity of training as an essential component of training for any athlete\textsuperscript{14}.

This notion of specificity is likely to have also contributed to other kinematic and kinetic adaptations made by the drop landing training group, including greater plantar-flexion at initial foot-ground contact, which increased the total ankle ROM and increased the duration of the load absorption time of the landing. Trained paratroopers have been found to increase plantar-flexion at initial foot-ground contact during higher velocity landings (from higher heights) relative to lower landing velocities, a strategy thought to attenuate increases in landing forces\textsuperscript{5, 27}. Although not significant ($p = 0.075$), the drop landing training group in the present study decreased their VGRF by approximately $1/2$ BW. There was also a strong trend to reduce the magnitude of their ATF at the time of the peak dorsiflexion angle (by $1/4$ BW) post-intervention compared to before the training. Furthermore, the reduction in ATF was at the end of the load absorption phase of the landing, when the strain would be at its largest. Consequently, task-specific drop landing training altered neuromuscular control of ankle dorsiflexion...
in these participants and, therefore, may have decreased the magnitude of the forces they encountered during landing.

A limitation of the current study was the low participant numbers per training group, coupled with high variability in outcome variables characterising ankle biomechanics, which is likely to have masked some statistically significant between-group differences. Nonetheless, the significant changes in the drop landing technique displayed by both the stretch and drop landing training groups, as well as the significant changes in DROM of the stretch-trained group, indicate that both task specific drop landing and stretch training may provide biomechanical advantages to the drop landing movement. There is sufficient evidence to warrant further investigation of these findings using a study design with higher power. It must also be acknowledged that performing stretch or strength training without concurrently performing landing specific training may be sub-optimal for decreasing plantar-flexor MTU loading and strain during landings. The notion that combining stretch training to increase DROM, with landing specific training to optimise landing mechanics and best utilise the increased passive DROM, should therefore be explored further.

CONCLUSIONS

Following training, participants in the drop landing training group adopted a neuromechanical landing strategy that resulted in more synchronous myoelectric activity in LG and MG during the peak load absorption time, a larger dynamic ankle ROM and an extension in the overall time taken to absorb the landing forces. The increase in passive DROM and the reduction in the dynamic dorsiflexion range used during the drop landing in the stretch group are postulated to have decreased strain on the entire plantar-flexor MTU. It was concluded that landing-specific training and
stretch training may each be beneficial for injury prevention by providing more synchronised muscular activation or by reducing plantar-flexor MTU strain during landing movements in sport. Further research is needed, however, to assess the prospective efficacy of such strategies in reducing the incidence of overuse and acute type strain injuries to specific anatomical structures such as the Achilles tendon and plantar-flexor muscles.

REFERENCES


Chapter 7

Summary, conclusions and recommendations for future research

SUMMARY

Reduced passive dorsiflexion range of motion (DROM) is associated with injury risk, particularly during landing tasks involving rapid dorsiflexion and elongation of the plantar-flexor muscle-tendon unit (MTU). Possible determinants of DROM, such as plantar-flexor MTU stiffness, as well as the potentially injurious biomechanical mechanisms associated with low DROM during landing movements, are poorly understood. Studies have reported conflicting results regarding both DROM and plantar-flexor stiffness changes as a result of training and the effects of training on ankle biomechanics during landings is yet to be investigated. Therefore, the primary purpose of this thesis was to determine whether variations in ankle dorsiflexion ROM affected ankle biomechanics during a drop landing task and whether these effects were moderated by training designed to modify dorsiflexion ROM.

A randomised controlled trial study was conducted, where 48 male volunteers underwent biomechanical assessment before and after a 6-week training intervention (either stretch training, eccentric strength training, task-specific landing training or control). Baseline and post-intervention assessments included measurements of passive DROM, passive plantar-flexor stiffness and ankle biomechanics during a single-limb drop landing task. Data collection for the outcome variables characterising landing biomechanics included EMG from four shank muscles and three-dimensional kinematics of the foot and shank as participants landed on a force platform. These biomechanical data provided input for inverse dynamic calculations of ankle kinetics and an estimation of Achilles tendon force generated during landing.
In Part I (Chapter 2), due to disparities in the literature regarding joint flexibility measurement techniques and their relationships, different baseline measures of DROM and plantar-flexor stiffness were compared for all 48 participants. It was hypothesised that non-weight-bearing measures of ankle DROM and passive stiffness would be significantly and strongly correlated, although poorly correlated with weight-bearing DROM, which was considered to be functionally relevant to dorsiflexion during a weight-bearing landing task. It was found that weight-bearing and non-weight-bearing assessments of DROM were not strongly correlated and that passive plantar-flexor stiffness was not highly correlated with either assessment of DROM. These findings suggest that passive plantar-flexor stiffness may not be a strong determinant of DROM. Furthermore, the functional capacity of the talocrural joint to cope with dorsiflexion during weight-bearing tasks may be underestimated or even misrepresented by non-weight-bearing measures of DROM. Therefore, although ankle DROM and plantar-flexor MTU stiffness may be implicated in injury risk during weight-bearing tasks such as landings, it may be due to different mechanisms.

Based on the results of Chapter 2, Part II of the thesis (Chapters 3 and 4) investigated the effect of DROM and plantar-flexor stiffness on ankle biomechanics during drop landings, as indicated by measures characterising load and strain. In Chapter 3 it was hypothesised that individuals with low passive DROM would display less dorsiflexion and incur higher ground reaction forces and higher plantar-flexor loads during the drop landing task than individuals with high passive DROM. Despite a large between-group difference in DROM (low DROM: 37.7 ± 2.5°; high DROM: 48.4 ± 2.5°), and in contrast to the original hypotheses, outcome variables describing ankle biomechanics during drop landings were very similar between the two groups. The finding indicated that landing strategies displayed by the participants in this study were
moderated more by the demands of the task than they were by the DROM available at the talocrural joint. The implications for injury potential in athletes with a low DROM, however, are that these athletes may be absorbing landing loads with their plantar-flexor MTU in a more extended and therefore physiologically compromised length. This may expose these athletes to an increased risk of both acute and repetitive overuse strain injuries, particularly in the plantar-flexor MTU.

Chapter 4 investigated the effects of plantar-flexor stiffness on drop landing technique, particularly with respect to variables used to describe loads and strains imposed upon the ankle and plantar-flexor MTU, in an attempt to better understand associations between plantar-flexor stiffness and potential injury risk. It was hypothesised that the high passive plantar-flexor stiffness group would display significantly less dorsiflexion, generate significantly higher ground reaction forces and experience significantly greater plantar-flexor MTU loading during the drop landings compared to the low passive plantar-flexor stiffness group. The results of the study revealed that both participant groups displayed very similar ankle biomechanics during the drop landings, indicating little effect of plantar-flexor stiffness on landing technique. Each group also had very similar passive DROM values. It was concluded, therefore, that low or high plantar-flexor stiffness would not affect the magnitude of plantar-flexor MTU strain and subsequent strain injury risk during the drop landing task.

Training interventions designed to increase DROM have been studied extensively, albeit with contrasting findings regarding effectiveness. The effects of training aimed at increasing DROM, particularly with respect to functional consequences such as ankle biomechanics during weight-bearing tasks like landings, are even less well understood. Due to the high incidence of plantar-flexor MTU strain and ankle injuries during landing sports and the association between having a low DROM and many of these
injuries, it is imperative that we gain a better understanding of training designed to increase DROM. Therefore, Part III of the thesis (Chapters 5 and 6) aimed to investigate the effect of different training methods on DROM and plantar-flexor stiffness and whether these different training methods moderated drop landing biomechanics of the ankle and plantar-flexor MTU.

The purpose of Chapter 5 was to determine and compare the effects of static stretch, eccentric strength and task-specific drop landing training on DROM and plantar-flexor stiffness. It was hypothesised that static stretch, eccentric strength and landing-specific training programs would all increase DROM and decrease passive plantar-flexor stiffness, irrespective of any changes in eccentric plantar-flexor strength. Results of the study revealed that stretch and eccentric strength training of the plantar-flexor MTU significantly increased DROM, although stretch training was the more effective training stimulus. The task-specific drop landing training and control groups displayed no significant changes in DROM. Passive plantar-flexor MTU stiffness was unaffected by any of the training protocols and was also unchanged in the control group post-intervention. It was concluded that for a training program designed to increase DROM, without necessarily altering MTU stiffness, then long-term static stretch training was the most effective method.

The final study of this thesis (Chapter 6) aimed to determine, through a randomised controlled trial, the effects of static stretch training, eccentric strength training and task-specific landing training on ankle biomechanics during a drop landing task. It was hypothesised that each method of training; stretch, eccentric strength and task-specific landing, would significantly change the neuromuscular and biomechanical strategies used by participants during a drop landing task. Post-intervention, participants in the stretch group coupled their increase in passive DROM (evident in Chapter 5) with
a reduction in the dynamic dorsiflexion range they used during the drop landing and this is postulated to have decreased strain on the entire plantar-flexor MTU. Although eccentric strength training significantly increased DROM and significantly increased peak eccentric strength, this training method did not affect landing technique. It was concluded that eccentric strength training was unlikely to alter ankle or plantar-flexor loading or plantar-flexor MTU strain during drop landings. Post-intervention, participants in the drop landing training group adopted a neuromechanical landing strategy that provided greater activation synchronicity between the plantar-flexor muscles, a larger dynamic ankle ROM and an extension in the overall time taken to absorb the landing forces. The significant changes in drop landing technique displayed by the stretch and task-specific drop landing training groups, together with a significant increase in DROM for the stretch group, indicate that both these training methods may provide biomechanical advantages that decrease injury risk for individuals participating in landing sports.

CONCLUSIONS

Ankle biomechanics during a drop landing is moderated by the demands of the task rather than an individual’s weight-bearing DROM or non-weight-bearing passive plantar-flexor stiffness. However, athletes with a low DROM, relative to the demands of the task, may be absorbing landing loads with their plantar-flexor MTU in a more extended length, thereby exposing them to an increased risk of both acute and repetitive overuse plantar-flexor MTU strain injuries. If athletes are considered to have a low DROM, long-term static stretch training can be recommended as it is more effective than eccentric strength or task-specific landing training in terms of increasing DROM. Static stretch training also appears to provide some biomechanical advantages during
drop landings, with respect to injury mechanisms, by potentially reducing plantar-flexor MTU strain. Specificity provided by landing training may also offer protection from injury during drop landings by altering plantar-flexor muscle coordination and control of the movement and by increasing the time over which to absorb the potentially injurious loads generated during such high impact landing tasks.

RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the studies conducted for this thesis the following recommendations for future research are made:

- As weight-bearing and non-weight-bearing measures of DROM are each poorly associated with plantar-flexor MTU stiffness, further research is required to determine how different structural components within the talocrural joint and plantar-flexor MTU behave mechanically during these different tasks used to assess flexibility. Researchers need to better understand how anatomical components within the plantar-flexor MTU contribute to mechanical behaviour of the ankle joint during controlled dorsiflexion movements, in order to direct future research into plantar-flexor MTU biomechanics during functional tasks.

- Passive DROM had little effect on ankle biomechanics during the drop landings studied in this thesis, although low DROM may lead to greater plantar-flexor strain and increased injury risk during landings. Further research is required to investigate how the different MTU structures which contribute to DROM, respond to loads and strains during landing movements in order to better understand injury potential. By determining the mechanical behaviour of specific anatomical structures within the plantar-flexor MTU during landings and better understanding their function and injury potential, researchers will be
able to conduct better-informed prospective research to assess injury incidence in athletes using targeted screening techniques.

- Plantar-flexor stiffness had little effect on ankle biomechanics during the drop landings studied for this thesis and, therefore, may not have affected strain magnitudes within the entire plantar-flexor MTU. It is reasonable to postulate, however, that the in-vivo stress experienced by plantar-flexor tissues in participants with a high passive MTU stiffness may have been affected by their inherently higher stiffness. Therefore, the effects of excessive plantar-flexor stiffness on in-vivo stresses during landing tasks requires further investigation, before strong conclusions regarding injury potential can be made.

- The assessment of the effects of passive stiffness on a dynamic landing movement involved muscular activation and it was acknowledged that the stiffness of the activated plantar-flexor MTU during the landing task in the present study may have been augmented. The magnitude of inherent stress experienced by each group during the landing task, however, was not determined and may be of more importance than the magnitude of strain. This argument remains speculative, however, and requires further investigation.

- Although stretch training was effective at increasing DROM, further research is required to assess the effects of increasing DROM on anatomical structures such as the Achilles tendon and the plantar-flexor muscles. Stretch training may also provide biomechanical protection from plantar-flexor MTU strain type injuries during drop landings; however, prospective research is required to assess the efficacy of long-term static plantar-flexor stretch training on reducing the incidence of these injuries in athletes engaged in regular landing activities.
Task-specific landing training may also offer protection from injury during drop landings through a combination of biomechanical changes that appear to provide greater control and may, therefore, reduce the magnitude of the forces sustained in and around the ankle joint. Prospective studies are required, however, to more accurately assess the long-term efficacy of landing training in reducing loading and injury incidence. Further research should also include an investigation of the cost-benefit of this type of training, in terms of the effects of repetitive loading and straining in and around the ankle joint.

Although static stretch training increases DROM and may provide some protective advantage during drop landings, it must be acknowledged that the effects of stretch training may be optimised by performing concurrent landing specific training as well. The notion that combining stretch training to increase DROM, with landing specific training designed to optimise landing mechanics and best utilise the increased passive DROM, should therefore be further investigated.