A person is shown in a laboratory setting, wearing a harness and motion capture markers. They are standing on a force plate, which is part of a larger experimental setup. The person is wearing a dark tank top and shorts, and has several reflective markers attached to their body. The background shows various pieces of laboratory equipment, including a force plate, a harness, and a computer monitor displaying data. The overall scene is brightly lit, and the person appears to be in the middle of an experiment or a demonstration.

What factors affect patellar tendon loading during landing?  
Implications for patellar tendinopathy.

Final Report to NSW Sporting Injury Committee



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## OVERVIEW

Patellar tendinopathy is a insidious knee injury with a high prevalence in sports involving repetitive vertical jumping together with high speed and power demands, such as volleyball<sup>[1-3]</sup>, basketball<sup>[1, 3, 4]</sup> and soccer<sup>[1, 3]</sup>. As there is a high incidence of patellar tendinopathy in a broad range of sports, practical strategies to reduce the incidence and severity of this injury in a diverse variety of sporting communities need to be developed. In order to identify what characteristics of an athlete's landing technique contribute to an increased risk of athletes developing patellar tendinopathy, the characteristics of an athlete's landing technique and how patellar tendon loading changes during landing in asymptomatic healthy athletes needs to be firstly established. Once established, investigation into risk factors associated with patellar tendinopathy such as, fatigue can then be investigated. This study aimed to characterise an athlete's landing technique and how patellar tendon loading changed when asymptomatic healthy athletes landed using a stop-jump movement (SJ), and how these biomechanical factors were moderated by fatigue.

Twenty-three skilled male soccer, basketball and volleyball players were recruited as subjects. All subjects underwent a patellar tendon ultrasound and a laboratory-based biomechanical assessment of a stop-jump movement (SJ). The results for 16 subjects (mean age =  $22.4 \pm 2.9$  years; height =  $182.1 \pm 8.7$  cm; mass =  $75.7 \pm 10.1$  kg), who had no patellar tendon ultrasonographic abnormality, were analysed. The patellar tendon force, ground reaction force, kinematic and muscle activity variables were analysed using paired *t*-tests to determine whether there were any significant ( $p \leq 0.05$ ) differences in the variables between the two landing phases within the SJ (horizontal and vertical) and the two fatigue conditions (non-fatigued and fatigued).

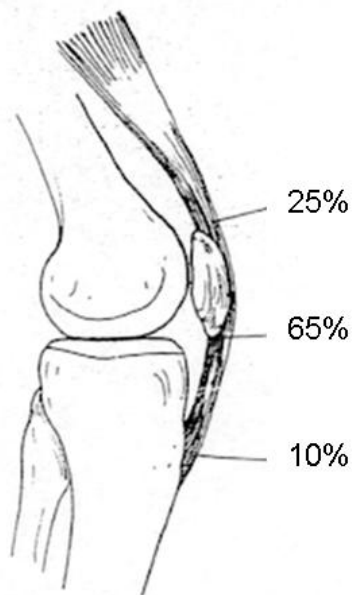
When comparing the landing phases in a SJ, subjects landed with significantly less vertical GRF; greater peak  $F_{PT}$ ; higher vertical GRF loading rates; less ankle plantar flexion at initial contact; greater ankle dorsiflexion at peak vertical GRF; greater knee and hip flexion; and earlier onset of tibialis anterior, vastus medialis and vastus lateralis muscle activity relative to initial contact in the horizontal landing phase compared to the vertical landing phase. In addition, when fatigued, subjects recorded significantly decreased peak  $F_{PT}$ ; increased vertical GRF loading rates; decreased knee and hip flexion; and decreased approach speed in the horizontal landing although only a significantly later onset of tibialis anterior and hamstring muscle activity in the vertical landing phase compared to landing in a non-fatigued state.

Vertical and horizontal landing movements require significantly different segmental kinetics, kinematics and muscle activation patterns resulting in significantly different  $F_{PT}$ . Additionally, although fatigue has been linked to lower limb injury and is a potential risk factor of patellar tendinopathy via affecting load dissipation efficiency, the effects of fatigue appear movement dependent. That is, fatigue only caused subjects in the present study to modify their landing mechanics when they performed the horizontal phase of the SJ. Therefore, landing movements that incorporate a horizontal phase may place athletes at greater risk of developing patellar tendinopathy than movements that incorporate purely vertical movements. However, as the actual patellar tendon forces decreased in the horizontal phase when fatigued, further research is required to confirm or refute these findings and associate horizontal movements with the onset of patellar tendinopathy. However, these results have important implications for future landing studies as many studies investigating lower limb injuries, particularly patellar tendinopathy have attempted to draw conclusions from a single movement task, such as a vertical drop landing. Further research is also warranted to determine the extent to which other risk factors associated with patellar tendinopathy such as, presence of a patellar tendon ultrasonographic abnormality, affect landing mechanics and injury incidence so that practical injury prevention strategies to reduce the incidence and severity of this injury in a diverse variety of sporting communities can be developed.

## INTRODUCTION

### *What is patellar tendinopathy?*

Patellar tendinopathy, commonly known as “jumper’s knee”, patellar tendinitis or patellar tendinosis, is any micro-tearing along the knee extensor mechanism. This micro-tearing can occur anywhere from the quadriceps tendon insertion on the upper pole of the patella to the proximal patellar tendon insertion on the inferior pole of the patella and/or to the distal patella ligament insertion on the tibial tuberosity<sup>[14, 15]</sup> (see Figure 1). Individuals typically experience pain on the anterior aspect of the patella and tenderness on palpation of the patellar tendon. Although the injury is self limiting<sup>[16]</sup>, it can impair an athlete’s performance by reducing training and competition levels for long time periods<sup>[1]</sup>, severely limiting or even ending athletic careers<sup>[1, 16]</sup>. Most athletes with patellar tendinopathy have continued playing their sport with the associated symptoms for several years<sup>[1]</sup>, with rest offering only temporary pain relief and pain typically returning with resumption of activity<sup>[16]</sup>. Surgical outcomes for patellar tendinopathy are poor and unpredictable. For example, a 4-year follow-up from surgical intervention for patellar tendinopathy revealed that, following surgery, only half of the subjects were competing at their pre-surgery sporting levels<sup>[17]</sup>. Despite substantial pathological and histological evidence pertaining to patellar tendinopathy in the literature, there is limited research on the specific intrinsic and/or extrinsic factors that increase the risk of patellar tendinopathy<sup>[18-22]</sup>. In order to decrease the incidence and severity of patellar tendinopathy within sporting communities, via effective prevention and/or treatment regimes, knowledge of risk factors that contribute to the injury incidence and severity require urgent investigation.



**Figure 1:** Location of pain in patellar tendinopathy (adapted from Ferretti et al.<sup>[23]</sup>, p 133).

### *Does excessive repetitive loading increase the risk of patellar tendinopathy?*

Of all the intrinsic and extrinsic risk factors associated with patellar tendinopathy, the main risk factor for this injury has been identified as a high frequency of repetitive jumping<sup>[14, 15, 24]</sup>. Activities involving rapid acceleration, deceleration, jumping and landing, place large loads on the extensor mechanism<sup>[25]</sup>, as the extensor muscles act to dissipate the kinetic energy generated during landing<sup>[26]</sup>. It is this high eccentric and impulsive loading placed on the extensor mechanism during repetitive jumping and landing that is involved in the aetiology of patellar tendinopathy<sup>[18, 27]</sup>.

In jumping, the patellar tendon may sustain forces of up to 8,000 N compared to only 500 N typically developed during walking<sup>[28]</sup>. Richards et al.<sup>[19]</sup> reported that ground reaction forces

generated during the spike jump landing in volleyball (5.6 - 6.0 times body weight) were approximately double those recorded during the spike jump take-off, the block jump landing, or running. It is postulated that the larger ground reaction forces generated during the spike jump landing would increase the patellofemoral joint load and may cause the patella to move into an unfavourable position. However, no research was located to identify which biomechanical factors affect patellar tendon forces generated during landing in soccer, basketball or volleyball or how these factors are moderated by fatigue.

Two studies were located which attempted to predict patellar tendinopathy in elite volleyball players<sup>[19, 22]</sup>. Richards et al.<sup>[19]</sup> found an association between greater knee flexion during landing with the injury, suggesting that when players land with their knees more flexed, it may increase patellar tendon tension, contributing to the development of patellar tendinopathy. A more recent study<sup>[22]</sup> found that a significant predictor of patellar tendinopathy was a greater foot inversion moment during landing of the spike jump. Combining the results of these two studies, Richards et al.<sup>[22]</sup> claimed that predictors of patellar tendinopathy included a high ground reaction force at landing, a high rate of extensor moment development, deep angles of knee flexion during landing, a knee external moment during take-off and greater foot inversion moment during the landing. Although providing some insight into possible factors contributing to patellar tendon loading, both studies were restricted to elite indoor volleyball players and therefore may not be applicable to other athletes of varying skill levels competing in sports other than volleyball. Furthermore, no research was located that has examined the loads the patellar tendon must withstand during a dynamic landing upon which we can identify specific biomechanical variables of a player's landing technique that may exacerbate patellar tendon forces, or how these factors are moderated by fatigue.

### *Why may fatigue increase patellar tendon loads sustained during a dynamic landing?*

Fatigue has been linked to lower limb injury<sup>[29-32]</sup> and is another potential factor that may affect the ability of the lower limb to efficiently dissipate the loads sustained during landing and, in turn, lead to an increase in patellar tendon loading. Fatigue is known to decrease muscle performance in landing tasks, partially as a result of less efficient use of elastic energy and fatigued muscles that are less able to absorb repetitive shock or stress. As the patellar tendon already sustains high loads during repetitive jumping activities, a decreased ability of the lower limb muscles to absorb the shock, as a result of fatigue, may contribute to the development of patellar tendinopathy by increasing the repetitive shock or stress transferred to the patellar tendon during landing. As patellar tendinopathy has been associated with a greater knee flexion angle<sup>[19]</sup> and foot inversion moment during landing<sup>[22]</sup>, these factors, which may be exacerbated when athletes perform landing movements when fatigued, may increase patellar tendon loading. Therefore, fatigue may indirectly increase the risk of developing patellar tendinopathy by potentially leading to greater patellar tendon force. However, no research was located to identify the effect of fatigue on patellar tendon forces during a dynamic landing and, in turn, implications for developing patellar tendinopathy.

## AIMS & HYPOTHESES

### *What did we aim to achieve?*

In order to assist in reducing the incidence and severity of patellar tendinopathy across the sporting community, the purpose of this study was to identify which biomechanical characteristics of an athlete's landing technique contribute to high patellar tendon loading during landing and how these biomechanical factors are moderated by fatigue.

## What did we hypothesise?

Based on previous literature, we hypothesised that:

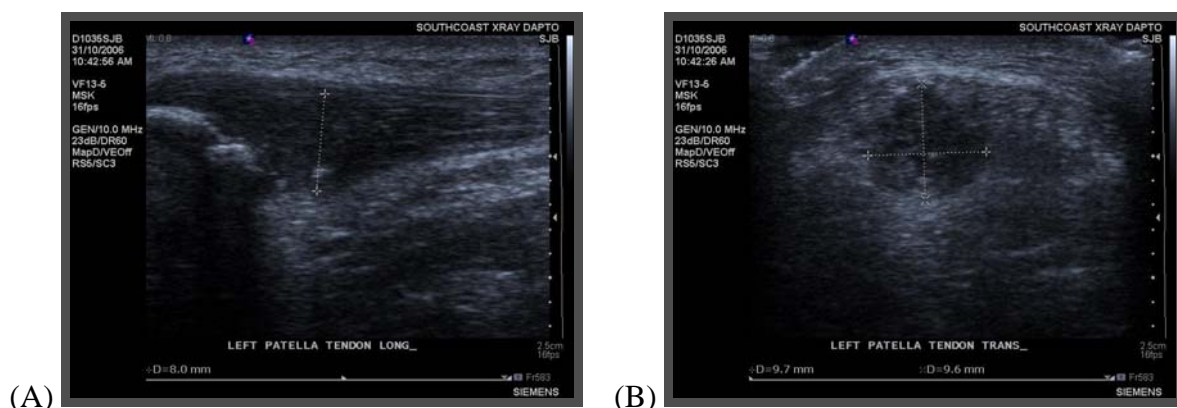
- (1) the horizontal landing phase within a stop-jump movement will be characterised by significantly different patellar tendon forces, ground reaction forces, changes in lower limb alignment and motion, and altered lower limb muscle activation patterns compared to the vertical landing phase; and
- (2) fatigue induced by repetitive jumping will result in higher patellar tendon loading, higher ground reaction forces, changes in lower limb alignment and motion, and altered lower limb muscle activation patterns compared to when non-fatigued during landing.

## METHODS & PROCEDURES

### Subjects

Twenty-three skilled male basketball, soccer or volleyball players (mean age =  $23.7 \pm 4.0$  years; height =  $183.0 \pm 6.2$  cm; mass =  $82 \pm 10.4$  kg) of a variety of skill levels, with no history of traumatic lower limb injuries, were recruited as subjects for the study. Subjects were restricted to players between 18 and 35 years of age as tendon quality degenerates with age. Written informed consent was obtained from each player prior to data collection and all testing was conducted according to the NHMRC Statement on Human Experimentation<sup>[33]</sup>. As subjects served as their own controls, no control subjects were required. Additionally, as patellar tendinopathy is twice as prevalent in male athletes compared to female athletes<sup>[1, 34]</sup>, this study focused on male athletes.

It has been hypothesised that another risk factor associated with developing patellar tendinopathy is an asymptomatic patellar tendon ultrasonographic abnormality (PTA)<sup>[35-37]</sup>. A PTA is defined as either a hypoechoic region evident on both a longitudinal and transverse ultrasound scan or fusiform swelling without hypoechoic areas<sup>[36]</sup> (see Figure 2). The clinical importance of a PTA has not yet been clarified<sup>[2]</sup>, as PTA has not been directly related to symptoms of patellar tendinopathy<sup>[2, 46, 48, 51]</sup>. However, presence of a PTA has been observed in athletes with patellar tendinopathy<sup>[2, 17, 38-45]</sup> and is higher in athletes than non-athletic individuals<sup>[2, 46]</sup>. As it is unknown whether asymptomatic athletes with a PTA utilise a particular landing strategy that may increase their risk of developing patellar tendinopathy, all subjects had both legs screened by a qualified ultrasonographer, Sue Beattie (South Coast X-Ray, Dapto, NSW), using an Antares with 13 MHz linear array (Siemens AG, Germany) to determine the presence of a PTA. Therefore, of the 23 recruited subjects, only the results for 16 subjects (mean age =  $22.4 \pm 2.9$  years; height =  $182.1 \pm 8.7$  cm; mass =  $75.7 \pm 10.1$  kg), who had no PTA, were analysed.



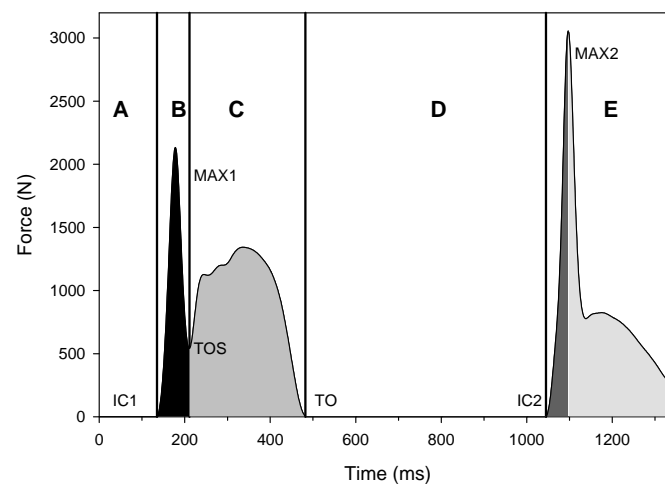
**Figure 2:** Ultrasound of a patellar tendon abnormality (PTA) defined as a hypoechoic region evident on both (A) longitudinal and (B) transverse ultrasounds.

## Experimental protocol

Testing was conducted over three testing sessions during a two week period. Day 1 involved each subject undergoing a familiarisation of the fatigue protocol in the Biomechanics Research Laboratory (BRL), University of Wollongong. Day 2 involved each subject undergoing an ultrasound assessment of both patellar tendons by a qualified ultrasonographer who evaluated their patellar tendon morphology. Within a week of Day 2, the subjects attended the BRL for Day 3 of data collection. Day 3 involved the collection of anthropometric data (including height, mass, and lower limb dimensions) following standard procedures<sup>[52]</sup> as later input into a mathematical model to allow us to predict the patellar tendon forces generated during the experimental movement. The subjects then performed five successful trials of a stop-jump movement that is typically performed within the three sports (basketball, soccer and volleyball) from which the subjects were drawn while kinematic, kinetic and muscle activation data were collected. The subjects were then fatigued and immediately after the fatigue protocol, five successful additional stop-jump movements were performed. The procedures describing the stop-jump movement, fatigue protocol and data collected during Day 3 of testing are described below.

## Stop-jump movement

A stop-jump movement (SJ) was chosen as the experimental task as soccer, basketball and volleyball players regularly perform this skill during a typical game and/or training. More importantly, the movement involves rapid acceleration and deceleration, placing large stresses on the knee extensor mechanism and, in turn, the patellar tendon. The SJ performed in this study involved a four step approach towards two force platforms with the subjects then performing a two foot landing, one foot on each force platform, jumping vertically upwards, followed by another two foot landing onto the force platforms. This movement comprised five phases: preparation phase, first landing phase (horizontal landing), take-off phase, flight phase and second landing phase (vertical landing). The exact transition between each of the five phases during each trial was determined using the vertical ground reaction force-time curves (see Figure 3).



**Figure 3:** The five phases of the stop-jump movement identified from vertical ground reaction forces include: (A) the preparation; (B) the first landing; (C) the take-off; (D) the flight; and (E) the second landing. IC1 = initial contact during the horizontal landing phase; MAX1 = peak vertical ground reaction force during the horizontal landing phase; TOS = first local minimum of vertical ground reaction force indicating transition between the horizontal landing phase and take-off of the vertical jump; TO = take-off; IC2 = initial contact during the vertical landing phase; and MAX2 = peak vertical ground reaction force during the vertical landing phase.

### Fatigue protocol

A fatigue protocol that utilises the typical muscle action performed throughout a soccer, basketball or volleyball game, and which enables us to evaluate the effects of fatigue on landing performance was developed. Movements performed during these sports, such as running and jumping, are frequently characterised by a stretch-shortening cycle (SSC) muscle action<sup>[53]</sup>, in which the patellar tendon is continually loaded. The fatigue protocol therefore included activities to simulate the demands of a SSC muscle action.

The fatigue protocol involved subjects completing a 5-10 minute warm-up on a cycle ergometer at a self-selected pace. Subjects were then familiarised with the SSC movement, which was performed on a sledge apparatus, inclined 23.6° from the horizontal (see Figure 4). This SSC movement entailed the subjects performing a series of bilateral submaximal rebound jumps to propel themselves along the gliding track of the sled fatiguing the major muscle groups of interest in a controlled, reliable and safe manner (see Figure 4). Once the subjects were familiarised with the exercise, they performed three maximum SSC exercises (100%) with 2 min rest between each effort. The subjects then repeatedly performed 30 submaximal SSC exercises (rebounding to 70% of their maximum SSC exercise height), followed by 30 s rest. Subjects continued to perform sets of SSC exercises until they could no longer maintain 70% of their maximum SSC exercise height. Immediately after completing this fatigue protocol, the subjects again performed five SJ in rapid succession. To confirm the level of player fatigue, two blood lactate samples were taken using an Acusport Analyser, one at rest and one following the fatigue protocol. The fatigue protocol has been previously validated and shown to reliably induce fatigue in male soccer, basketball and volleyball players<sup>[54]</sup>.



**Figure 4:** A subject performing the stretch-shortening cycle (SSC) exercise within the sledge apparatus during the fatigue protocol.

### Kinematic data

Each subject's motion during the SJ was recorded (100 Hz) from both the lateral and frontal aspects using an OptoTrak 3020 motion analysis system. For each lower limb, infrared emitting diodes were placed on the foot, leg, and thigh segments to enable the movement of these segments to be tracked. Two Position Sensors then sequentially sampled the mean centroid position of each marker so that the three-dimensional co-ordinates for each segment were stored on a personal computer for later analysis. The kinematic data were filtered using a fourth order zero-phase shift Butterworth (high-pass cut-off ( $f_c$ ) = 18 Hz) to eliminate any movement artefact and analysed

using Visual 3D software (Version 3, C-Motion, Maryland, USA). Kinematic variables were calculated from the processed data and included those variables required for later calculation of the patellar tendon forces, as well as ankle, knee and hip joint alignment and motion at initial foot-contact (IC) and at the time of the peak resultant ground reaction force ( $F_R$ ).

### Kinetic data

Three orthogonal components and the point of application of the ground reaction forces (GRF) of each lower limb were recorded during both landing phases using two 600 mm x 400 mm x 61 mm Kistler multichannel force platforms (Type 9281B; Type 9253B; Kistler, Winterthur, Switzerland) embedded in the floor and connected each to two multichannel charge amplifiers (Type 9865A; Type, 9865B; Kistler, Winterthur, Switzerland). Force data were sampled (1000 Hz) during the SJ for at least five successful trials (that is, landing with each foot in the middle of the respective force platform). For the data files for each force platform, the four vertical ( $F_V$ ), two mediolateral ( $F_{ML}$ ) and two anterior-posterior ( $F_{AP}$ ) force channels were summed and scaled to obtain force-time curves. The GRF data were used to determine the magnitude and timing of  $F_R$  and to determine the five phases of each SJ, described previously. The GRF, free moments and centre of pressure data were filtered using a fourth-order zero-phase-shift Butterworth digital low pass filter ( $f_c = 18$  Hz) before calculating individual knee joint moments and patellar tendon forces. Patellar tendon force was calculated by dividing the knee joint moment by the patellar tendon moment arm using the following equation:

$$F_{PT} = Mk/dp$$

where:  $Mk$  = the net muscle moment acting on the leg segment at the knee  
 $dp$  = the moment arm of  $F_{PT}$  relative to knee flexion based on Herzog & Read<sup>[55]</sup>

### Muscle activation patterns

Electromyographic (EMG) activity of rectus femoris (RF), vastus lateralis (VL), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), medial head of gastrocnemius (MG) and tibialis anterior (TA) were recorded for both lower limbs during the SJ. Following standard preparation<sup>[56]</sup>, bipolar silver-silver-chloride surface electrodes (Ambu<sup>®</sup> Blue Sensor M, electrode size = 40.8 x 32 mm, detection area = 13.2 mm) were placed longitudinally on each muscle belly (inter-electrode distance of 20 mm). A common reference electrode was located on the medial tibial tuberosity of each lower limb. Electrode potentials were relayed from the electrodes to two TeleMyo 900 battery powered transmitters strapped firmly to the subject's lower back, via leads. The EMG signals were then relayed from two transmitters to two TeleMyo 900 (Noraxon, U.S.A., Scottsdale AZ) receivers via two antennas connected to transmitters. The analog output for the seven muscles of both lower limbs from each receiver were recorded in real-time at 1000 Hz (bandwidth 10-500 Hz).

The raw EMG signals were filtered using a fourth order zero-phase shift Butterworth ( $f_c = 15$  Hz) to eliminate any movement artefact. To quantify temporal characteristics of the muscle bursts the filtered EMG data were full-wave rectified with a 20 Hz low pass filter to create linear envelopes that were then screened using a threshold detector (8% of the maximum amplitude) using custom EmgAnalysis Labview software (Labview 8, National Instruments). Each individual muscle's filtered EMG signal was visually inspected to confirm the validity of the calculated results to minimise the probability of a Type I error. Due to large between-subject variations in the muscle activation strategies utilised during the entire SJ and the resultant difficulty in comparing between subjects, muscle activity was only analysed for the first muscle burst of each muscle activated during each landing phase of the SJ. Therefore, the time from onset of muscle activity relative to IC and time of peak  $F_R$  (ms) were analysed for the seven muscles of each subject's lower limb during the horizontal and vertical landing phases of the SJ in the non-fatigued and fatigued conditions.

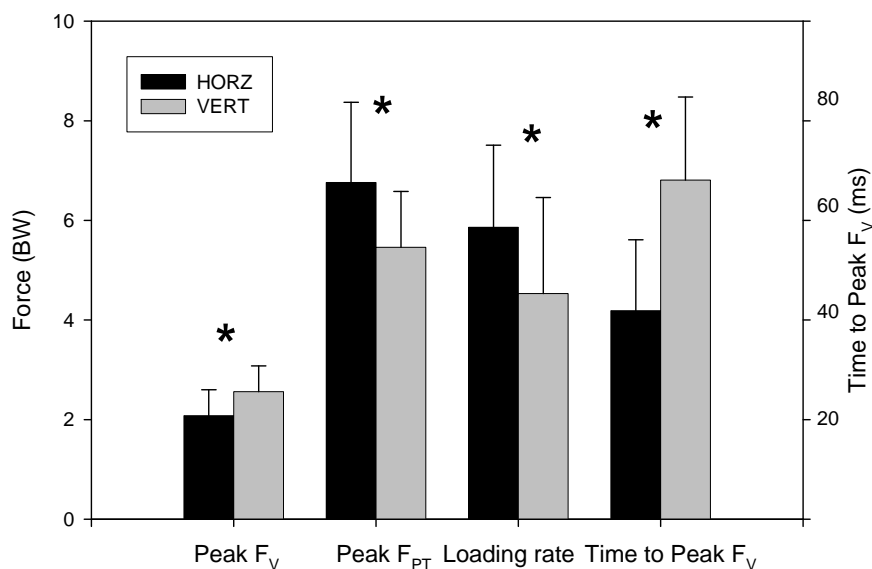
## Statistical analysis

Normality (Kolmogorov-Smirnov test with Lilliefors' correction) and equal variance (Levene Median test) of the data were initially confirmed. Means and standard deviations for the dependent variables (GRF, kinematic,  $F_{PT}$  and EMG data) for the SJ in both landings (first landing phase or horizontal landing (HORZ) and second landing phase or vertical landing (VERT)) were then calculated for the subjects. The GRF, kinematic,  $F_{PT}$  and EMG variables were then analysed using a paired  $t$ -test design. The purpose of this design was to determine whether there were any significant ( $p \leq 0.05$ ) differences in the variables between the two landing phases within the SJ (HORZ and VERT). In addition, as fatigue effects are task specific<sup>[11]</sup>, each landing phase was analysed individually using paired  $t$ -tests were also used to determine whether there were any significant differences between the two fatigue conditions (non-fatigued and fatigued). All statistical procedures were conducted using SPSS (Version 15.0).

# PART 1: CHARACTERISING THE LANDING PHASES OF A STOP-JUMP MOVEMENT

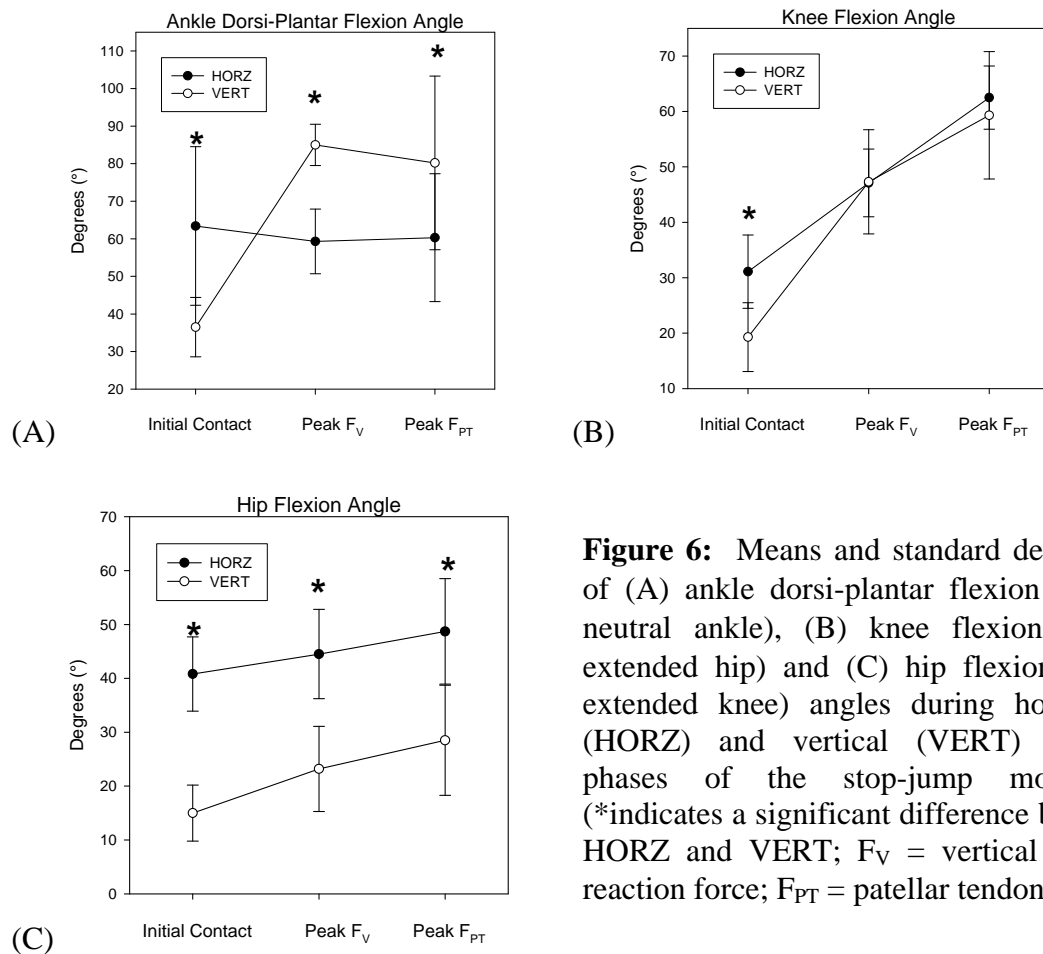
## Results

**Kinetic data:** The means and standard deviations for the GRF variables and peak  $F_{PT}$  generated during the two landing phases within the SJ are presented in Figure 5. During the HORZ, subjects generated a significantly lower mean peak  $F_V$ , took significantly less time to reach peak  $F_V$ , had a significantly higher  $F_V$  loading rate and recorded a significantly higher mean peak  $F_{PT}$  than during the VERT (see Figure 5). Previous studies investigating the HORZ in a SJ have reported similar<sup>[57-59]</sup> or lower<sup>[60, 61]</sup> peak  $F_V$  and a slightly faster time to peak  $F_V$ <sup>[58, 59, 61]</sup>. No studies investigating the SJ have reported any kinetic variables during the VERT. However, other studies investigating a vertical drop landing have reported similar<sup>[10, 61]</sup> or higher<sup>[11, 62]</sup> peak  $F_V$ , a higher  $F_V$  loading rate<sup>[10, 11]</sup> and a faster time to peak  $F_V$ <sup>[11, 62]</sup> compared to the data presented for the VERT in the present study. Peak  $F_{PT}$  data could not be located for the SJ.



**Figure 5:** Means  $\pm$  standard deviations for the peak vertical ground reaction (peak  $F_V$ ) and patellar tendon (peak  $F_{PT}$ ) forces during the horizontal (HORZ) and vertical (VERT) landing phases of the stop-jump movement (\*indicates a significant difference between HORZ and VERT).

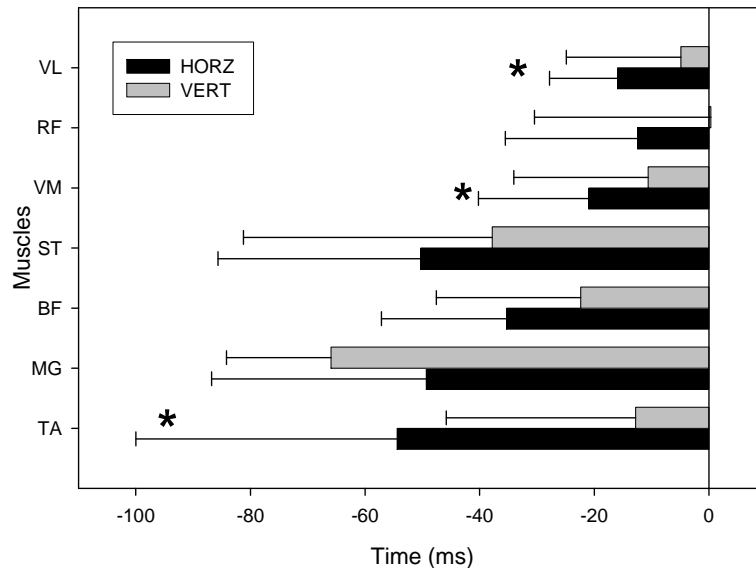
**Kinematic data:** The means and standard deviations for the ankle, knee and hip angles generated during the two landing phases within the SJ are presented in Figure 6. Accompanying the significant differences in the kinetic data, subjects displayed significantly different lower limb motion and alignment during the HORZ when compared to the VERT. That is, during the HORZ, subjects landed with significantly less ankle plantar flexion, greater knee and hip flexion at IC; and significantly greater ankle plantar flexion and hip flexion at peak  $F_V$  and peak  $F_{PT}$  compared to the VERT (see Figure 6). Previous studies investigating the HORZ in a SJ have reported similar knee angles<sup>[57-60, 63]</sup> and similar<sup>[60]</sup> or greater<sup>[59]</sup> hip angles. No studies investigating the SJ have reported any kinematics of the VERT. However, other studies investigating a vertical drop landing have reported similar<sup>[11, 62]</sup> or less<sup>[10]</sup> ankle plantar flexion, similar<sup>[10, 62]</sup>, less<sup>[11]</sup> or greater<sup>[61]</sup> knee flexion, and similar<sup>[10]</sup> or greater<sup>[61]</sup> hip flexion angles at IC to those recorded in the present study.



**Figure 6:** Means and standard deviations of (A) ankle dorsi-plantar flexion ( $90^\circ$  = neutral ankle), (B) knee flexion ( $0^\circ$  = extended hip) and (C) hip flexion ( $0^\circ$  = extended knee) angles during horizontal (HORZ) and vertical (VERT) landing phases of the stop-jump movement (\*indicates a significant difference between HORZ and VERT;  $F_V$  = vertical ground reaction force;  $F_{PT}$  = patellar tendon force).

**Muscle activation patterns:** The means and standard deviations for the onset of muscle activation generated during the two landing phases within the SJ are presented in Figure 7. Irrespective of landing type, in anticipation of the loads to be generated, the subjects used an anticipatory muscle activation strategy to stabilise their lower limbs at landing. However, the muscle recruitment order differed between the HORZ and VERT in the SJ. During the HORZ, subjects initially recruited TA then ST, MG and BF followed by the quadriceps muscles (VM, VL and RF). During the VERT, MG was initially recruited followed by the hamstring muscles (BF and ST), TA and lastly the quadriceps muscles (VM, VL and RF). When comparing the two landing phases of the SJ, subjects recorded a significantly earlier activation of VL, VM and TA during the HORZ compared to the VERT. Pre-programmed muscle recruitment strategies similar to those found in the present study for the HORZ have been reported for a deceleration task involving a single-limb landing to catch a ball<sup>[65, 66]</sup> and in a run and rapid stop movement<sup>[30]</sup>. However, in studies investigating

vertical drop landings, the data differed to those recorded for the VERT in the present study whereby MG has been initially recruited followed by the quadriceps muscles (RF and VL), and then either the hamstring (BF and ST)<sup>[11]</sup> or TA<sup>[62]</sup> muscles. No data were located in the literature pertaining to muscle activation patterns during a SJ, against which the present results could be directly compared. Despite high variability in the muscle recruitment patterns (see Figure 7), subjects activated their VL, VM and TA significantly earlier during performance of the HORZ compared to the VERT.



**Figure 7:** Muscle burst onset relative to initial contact (time = 0 s) during the (A) horizontal (HORZ) and (B) vertical (VERT) landings of the stop-jump movement (\*indicates a significant difference between HORZ and VERT; negative values indicated muscle activation before initial contact).

## Discussion

Despite excessive repetitive loading thought as the major extrinsic risk factors associated with patellar tendinopathy, only limited research was located that investigated patellar tendon loading during different movement tasks. No research was located that characterised an athlete's landing technique and how patellar tendon loading is altered when landing. The present study provides us with information about the characteristics of an athlete's landing technique and how patellar tendon load alters when landing in asymptomatic healthy athletes.

Most studies investigating patellar tendinopathy have used the peak  $F_V$  sustained during landing as representative of the forces the patellar tendon sustains. However, it has also been shown that two different movement tasks (squat and counter-movement jump) producing similar peak  $F_V$  produce very different peak  $F_{PT}$ <sup>[67]</sup>. In the present study, although the subjects sustained a significantly lower peak  $F_V$  in the HORZ, they recorded a significantly higher peak  $F_{PT}$  and the opposite was true during the VERT. These results indicate that there may not be a linear relationship between peak  $F_V$  and peak  $F_{PT}$ , and consequently, using the peak  $F_V$  sustained during landing as representative of the peak  $F_{PT}$  needs to be questioned. However, further research is required to confirm or refute the relationship between peak  $F_V$  and peak  $F_{PT}$ .

Many studies have utilised a vertical drop landing to investigate the lower limb landing mechanics in injuries such as patellar tendinopathy<sup>[10, 11]</sup>. Vertical drop landings isolate the landing phase from the whole jump task, standardising the land via the initial jump height. Despite the drop landing not being a common sport-related jump, these studies have extrapolated their results to a variety of landing activities in sports<sup>[7, 8, 10, 12, 13]</sup>. In the present study, the two landing phases (HORZ and VERT) within a SJ differed significantly from each other with respect

to the GRF, peak  $F_{PT}$ , lower limb alignment and the synchrony of the lower limb muscle activation patterns. These significant differences clearly indicate that the landing phases involve different segmental kinetics, kinematics and muscle activation patterns, reflecting the different task requirements between the HORZ and VERT landings. That is, vertical landing movements occur predominantly in the vertical plane with little horizontal shear forces evident whereas horizontal landing movements require dynamic stabilisation by the lower limb in both the vertical and horizontal planes. Consequently, research examining landing mechanics should take care not to make general statements about all landing movements based on the analysis of one movement type.

Although it remains unknown as to what biomechanical factors affect patellar tendon loads when landing in asymptomatic healthy athletes, use of a stiffer landing strategy<sup>[4,5,41,45]</sup> has been suggested to increase the risk of developing patellar tendinopathy by increasing patellar tendon tension. A stiffer landing strategy is indicated by landing with either greater knee extension forcing greater knee flexion<sup>[41,45]</sup> or a faster rate of landing<sup>[4,5,41,45]</sup>. During the VERT in the present study, subjects landed with less knee and hip flexion compared to the HORZ, indicative of a stiff landing strategy as evidenced by the high peak  $F_V$ . However, subjects also recorded a lower rate of loading evidenced by the longer time to peak  $F_V$  and a lower peak  $F_{PT}$ . The decreased loading rate and longer time to peak  $F_V$  may have been due to the greater range of motion experienced at the ankle ( $55^\circ$ ), knee ( $27^\circ$ ) and hip ( $43^\circ$ ) from IC to peak  $F_V$  (see Figure 6) of the VERT allowing them to better dissipate the higher GRF such that the peak  $F_{PT}$  was decreased. In the HORZ, the range of motion experienced from IC to peak  $F_V$  by the ankle ( $-5^\circ$ ), knee ( $15^\circ$ ) and hip ( $19^\circ$ ; see Figure 6) was much lower potentially leading to the greater peak  $F_{PT}$  sustained by subjects during this movement (see Figure 5). Therefore, landing with extended lower limb joints, defined as a stiff landing strategy, does not necessarily indicate greater loading of the patellar tendon and further research is warranted to investigate how lower limb motion affects patellar tendon loading and incidence of patellar tendinopathy.

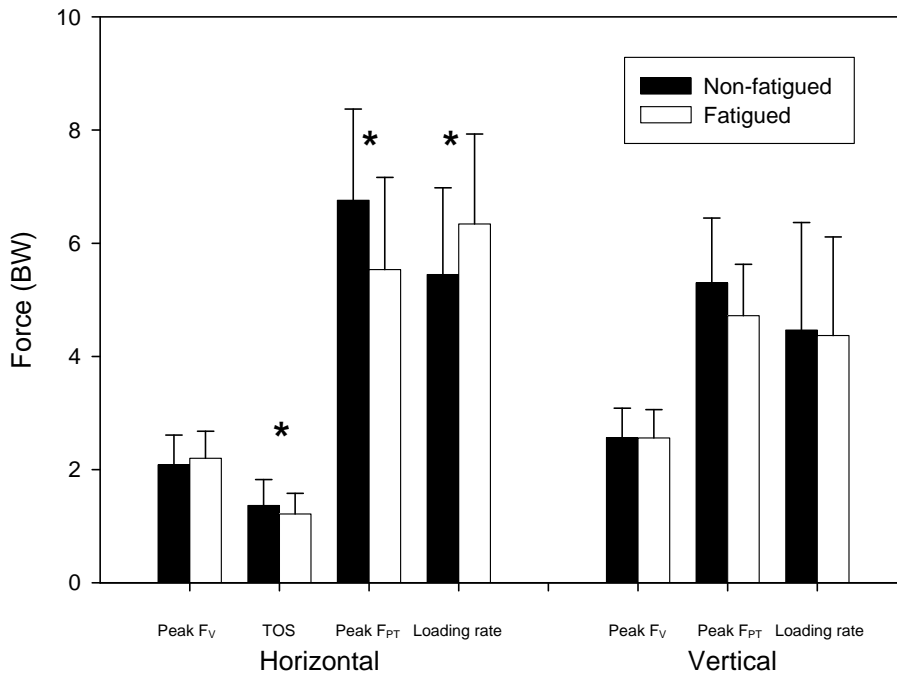
## PART 2: EFFECTS OF FATIGUE

### Results

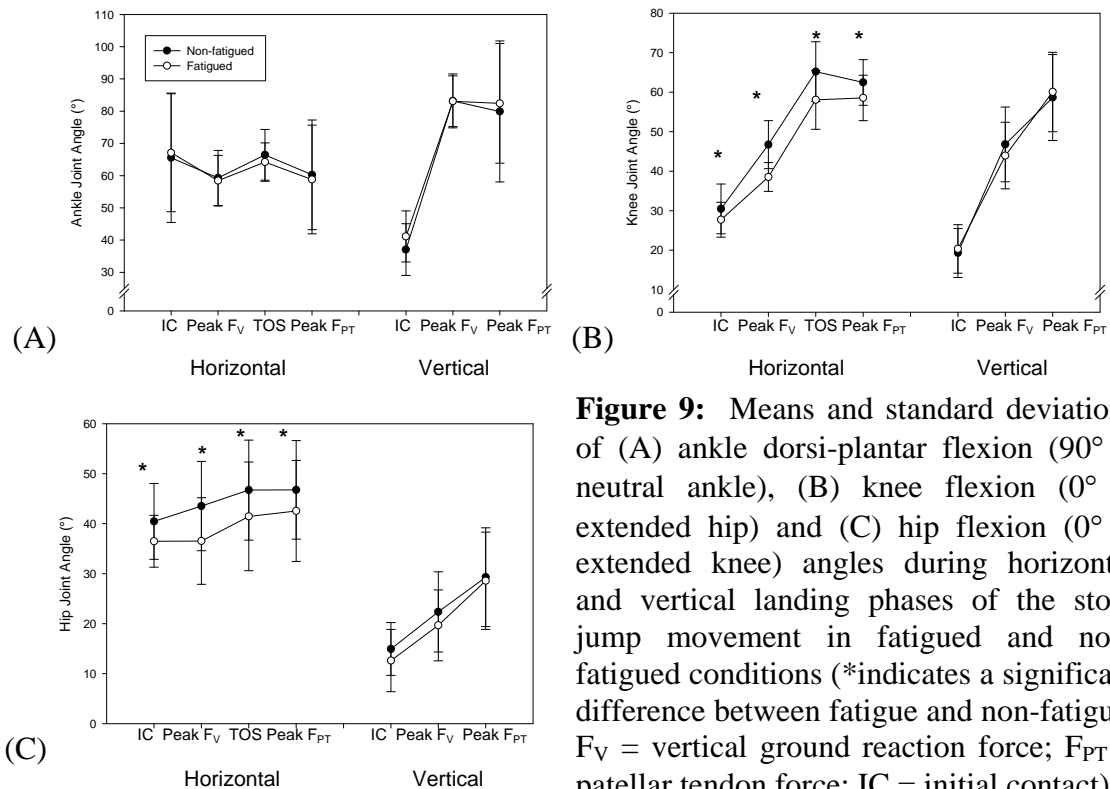
**Kinetic data:** The means and standard deviations for the GRF variables and peak  $F_{PT}$  generated during the two landing phases within the SJ for the fatigued and non-fatigued conditions are presented in Figure 8. During the HORZ, subjects recorded similar time to reach peak  $F_V$  and similar mean peak  $F_V$ , generated a significantly lower mean peak  $F_{PT}$  and had a significantly higher  $F_V$  loading rate when fatigued compared to non-fatigued. When fatigued and during the VERT, subjects recorded a similar time to reach the peak  $F_V$  and similar mean peak  $F_V$ , mean peak  $F_{PT}$ , and  $F_V$  loading rates compared to a non-fatigued condition. Only one previous study has reported that fatigue increased peak  $F_V$  in the horizontal landing phase of a SJ<sup>[68]</sup> whereas, although no studies have investigated the effects of fatigue in the vertical landing phase of a SJ, in vertical drop landings, fatigue has been shown to not affect<sup>[69]</sup> or decrease<sup>[70, 71]</sup> peak  $F_V$ .

**Kinematic data:** The means and standard deviations for the ankle, knee and hip angles generated during the two landing phases within the SJ in a non-fatigued and a fatigued condition are presented in Figure 9. When fatigued, subjects displayed significantly different lower limb motion and alignment during the HORZ compared to the non-fatigued condition. That is, when fatigued, subjects recorded a significantly slower approach speed (non-fatigued =  $4.5 \pm 0.4 \text{ m.s}^{-1}$ ; non-fatigued =  $4.1 \pm 0.5 \text{ m.s}^{-1}$ ;  $p < 0.002$ ) prior to the HORZ and a significantly lower vertical jump height (non-fatigued =  $48.6 \pm 0.5 \text{ cm}$ ; fatigued =  $45.1 \pm 0.6 \text{ cm}$ ;  $p < 0.001$ ) prior to the VERT than when non-fatigued. In addition, during the HORZ and when fatigued, subjects displayed significantly less knee and hip flexion than when non-fatigued. Interestingly, fatigue did not have

any significant effect on any of the kinematic variables during the VERT. Previous studies have reported a similar decreases in jump height and knee flexion when fatigued during a SJ in recreational athletes<sup>[63]</sup>. However, previous studies investigating the effects of fatigue in a vertical drop landing have reported unaltered ankle plantar flexion<sup>[6, 69, 71]</sup>, unaltered<sup>[6, 71]</sup> or decreased<sup>[69]</sup> knee flexion, and unaltered hip flexion<sup>[6, 71]</sup> angles when fatigued compared to non-fatigued.

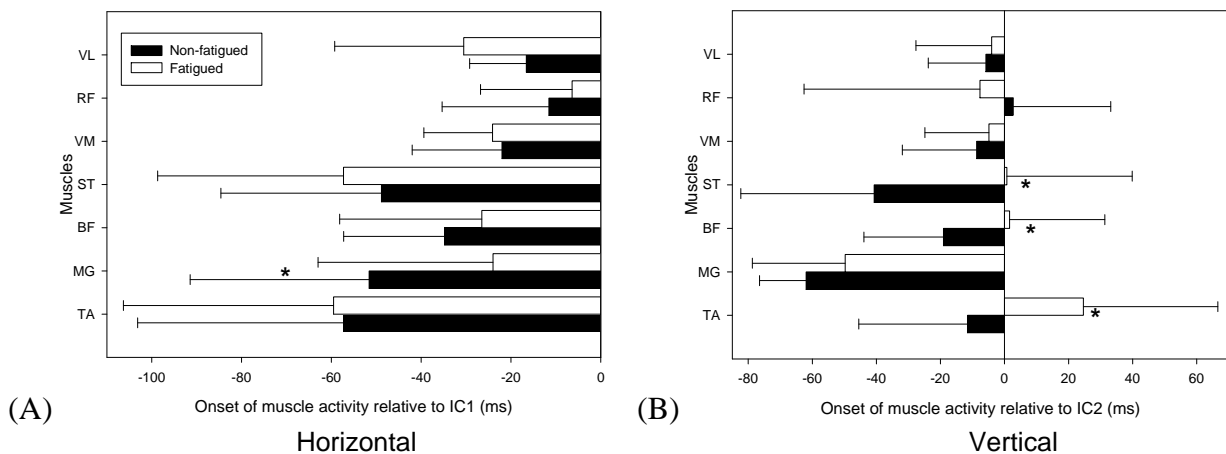


**Figure 8:** Means  $\pm$  standard deviations for the peak vertical ground reaction (peak F<sub>V</sub>) and patellar tendon (peak F<sub>PT</sub>) forces during the horizontal and vertical landing phases of the stop-jump movement between a non-fatigued and a fatigued condition (\*indicates a significant difference between fatigue and non-fatigue).



**Figure 9:** Means and standard deviations of (A) ankle dorsi-plantar flexion (90° = neutral ankle), (B) knee flexion (0° = extended hip) and (C) hip flexion (0° = extended knee) angles during horizontal and vertical landing phases of the stop-jump movement in fatigued and non-fatigued conditions (\*indicates a significant difference between fatigue and non-fatigue; F<sub>V</sub> = vertical ground reaction force; F<sub>PT</sub> = patellar tendon force; IC = initial contact)

**Muscle activation patterns:** The means and standard deviations for the onset of muscle activation generated during the two landing phases within the SJ in the fatigued and non-fatigued conditions are presented in Figure 10. When investigating the effects of fatigue in the present study, subjects altered their muscle recruitment strategy in both landing phases in the SJ between a non-fatigued and a fatigued condition. Compared to the muscle recruitment pattern displayed by the subject during performance of the HORZ in a non-fatigued condition (see Figure 7), subjects initially recruited TA then ST with VL, VM, BF and MG then activating at a similar time followed by RF. However, despite the slightly altered recruitment patterns, MG was the only muscle to be activated significantly later when fatigued compared to non-fatigued. During the VERT and when fatigued, MG was initially recruited followed by the quadriceps muscles (RF, VM and VL) with TA and the hamstring muscles (ST and BF) activating after IC. When comparing the fatigue and non-fatigue conditions for the VERT, TA, BF and ST were all activated significantly later relative to IC when fatigued compared to the non-fatigued condition. Few studies have investigated fatigue and horizontal landing movements. However, previous studies have similar reported a similar delay in the onset of BF and ST muscle burst activity in walking<sup>[72]</sup>, running and a rapid stop task<sup>[30]</sup>. An earlier VL muscle burst onset<sup>[53]</sup> or no change in any lower limb muscle recruitment patterns have also been reported when performing a vertical drop landing under a fatigued condition<sup>[69]</sup>.



**Figure 10:** Muscle burst onset relative to initial contact (time = 0 s) during the (A) horizontal and (B) vertical landings of the stop-jump movement in fatigued and non-fatigued conditions (\*indicates a significant difference between fatigue and non-fatigue; negative values indicated muscle activation before initial contact).

## Discussion

Fatigue has been linked to lower limb injury<sup>[29-32]</sup> and is it a factor that may affect the ability of the lower limb to efficiently dissipate the loads sustained during landing. During the HORZ, although fatigue did not alter peak  $F_v$ , subjects did significantly decrease their approach speed in the fatigue condition. It is postulated that if subjects were forced to keep their approach speed constant between the two conditions, peak  $F_v$  may have increased and further studies should consider this in their design. Fatigue did however, significantly increase the GRF loading rate and led to less knee and hip displacement from IC to peak  $F_v$ , indicating a decreased ability of the lower limb muscles to dissipate the loads sustained during this stiffer landing. As discussed in Part 1 above, a stiffer landing strategy has been suggested to increase the risk of developing patellar tendinopathy. However, as in Part 1, despite this stiffer landing peak  $F_{PT}$  significantly decreased when subjects performed the HORZ fatigued compared to the non-fatigued condition.

In contrast to the HORZ, fatigue did not alter any of the vertical GRF variables, peak  $F_{PT}$ , kinematic variables or muscle burst onset in MG or the quadriceps muscles during performance of the VERT. As MG acts eccentrically during a landing to control dorsiflexion and absorb and/or

dissipate impact forces, and VL and RF are important for knee joint stability, the lack of change in the onset of these muscles supports why fatigue did not alter the peak  $F_{PT}$ , GRF or kinematic variables in the VERT. Interestingly, fatigue did lead to delayed activation of the hamstring muscles and TA compared to the non-fatigued condition, causing a change in the muscle recruitment order. The fact that these muscles activated after IC may indicate a limited or altered role in force dissipation during the VERT as well as a limited contribution to patellar tendon loading. However, the change in TA and the hamstrings may have implications in other knee joint injuries, such as anterior cruciate ligament, as hamstrings (ST and BF) act primarily to flex the leg at the knee and extend the thigh at the hip<sup>[73, 74]</sup>, with ST acting to medially rotate the leg at the knee joint and thigh at the hip joint<sup>[74]</sup> and with BF acting to laterally rotate these lower limb segments, the hamstring balance the frontal and transverse plane loads<sup>[75]</sup>.

The inconsistent effect of fatigue on the biomechanics of landing, in particular muscle recruitment patterns, supports the research stating that fatigue effects are specific to the movement task performed<sup>[11]</sup>. In the present study, subjects were requested to perform maximally. However, when fatigued, subjects reduced both their approach speed and vertical jump height compared to the non-fatigued conditions. As these are real fatigue effects that are seen within the game conditions of many sports, they are important factors to consider and, if these variables were kept constant, the movements being studied may not be representative of natural sporting movements.

## LIMITATIONS OF THE STUDY

- (1) Subject recruitment was difficult due to the nature of the study investigating the effects of fatigue and the narrow subject selection criteria. Of the 28 subjects recruited, four subjects withdrew during the study due to not wanting to complete the fatigue protocol a second time (after the initial familiarisation session) due to temporary muscle soreness and one subject withdrew due to work commitments.
- (2) Subject activity outside the research study could not be controlled and throughout their involvement, subjects were tested in different phases of their sport from pre-season conditioning, in-season competition and post-season recovery (due to the longer than anticipated recruitment period and different sports). In addition, despite being encouraged not to complete heavy training sessions within 24 hours of the Day 3 testing session, some subjects did not adhere to recommendations.
- (3) Although being healthy active male athletes, the fitness and training status of each participant may have varied. However, this was not expected to affect the level of fatigue obtained by each subject, as this was individually standardised.
- (4) As the study was restricted to subjects who volunteered to participate, the sample was not a truly random sample of the wider population.
- (5) Despite being familiarised with the experimental procedure, participants may have varied their normal landing action when performing the SJ in a laboratory environment.
- (6) Standard methods for EMG preparation and data analysis were followed to minimise the expected cross-talk between lower limb muscles when using surface electromyographic procedures to assess muscle activity.

## CONCLUSIONS & FUTURE DIRECTIONS

Vertical and horizontal landing movements require significantly different segmental kinetics, kinematics and muscle activation patterns resulting in significantly different  $F_{PT}$ . Additionally, although fatigue has been linked to lower limb injury and is a potential risk factor of patellar

tendinopathy via affecting load dissipation efficiency, the effects of fatigue appear movement dependent. That is, fatigue only caused subjects in the present study to modify their landing mechanics when they performed the horizontal phase of the SJ. Therefore, landing movements that incorporate a horizontal phase may place athletes at greater risk of developing patellar tendinopathy than movements that incorporate purely vertical movements. However, as the actual patellar tendon forces decreased in the horizontal phase when fatigued, further research is required to confirm or refute these findings as well as investigate these variables in conjunction with other proposed risk factors such as jump frequency, work-rest periods, and/or patellar tendon abnormality. Increased research in this area will improve our understanding of what leads to the incidence of patellar tendinopathy enabling us to develop and prescribe practical injury prevention strategies to reduce the incidence and severity of this injury in a diverse variety of sporting communities.

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## REFERENCES

1. Lian, O.B., L. Engebretsen, and R. Bahr, *Prevalence of jumper's knee among elite athletes from different sports: a cross-sectional study*. American Journal of Sports Medicine, 2005. **33**(4): p. 561-567.
2. Gisslen, K., et al., *High prevalence of jumper's knee and sonographic changes in Swedish elite junior volleyball players compared to matched controls*. British Journal of Sports Medicine, 2005. **39**(5): p. 298-301.
3. Witvrouw, E., et al., *Intrinsic risk factors for the development of patellar tendinitis in an athletic population. A two-year prospective study*. American Journal of Sports Medicine, 2001. **29**(2): p. 190-195.
4. Hickey, G.J., *Injuries of young elite female basketball players over a six-year period*. Clinical Journal of Sport Medicine, 1997. **7**(4): p. 252-256.
5. Fagenbaum, R. and W.G. Darling, *Jump landing strategies in male and female college athletes and the implications of such strategies for anterior cruciate ligament injury*. American Journal of Sports Medicine, 2003. **31**(2): p. 233-240.
6. McLean, S.G., et al., *Impact of fatigue on gender-based high-risk landing strategies*. Medicine & Science in Sports & Exercise, 2007. **39**(3): p. 502-514.
7. McNitt-Gray, J.L., T. Yokoi, and C. Milward, *Landing strategy adjustments made by female gymnasts in response to drop height and mat composition*. Journal of Applied Biomechanics, 1993. **9**: p. 173-190.
8. McNitt-Gray, J.L., *Kinematics and impulse characteristics of drop landing from three height*. International Journal of Sport Biomechanics, 1991. **7**: p. 201-224.
9. Kovacs, I., et al., *Foot placement modifies kinematics and kinetics during drop jumping*. Medicine and Science in Sports and Exercise, 1999. **31**(5): p. 708-716.
10. Bisseling, R.W., et al., *Relationship between landing strategy and patellar tendinopathy in volleyball*. British Journal of Sports Medicine, 2007. **41**(7): p. e8.
11. Edwards, S., *The effects of fatigue on landing in Beach Volleyball: Implications for patellar tendinosis*, in *Department of Biomedical Science*. 2002, University of Wollongong: Wollongong.
12. Edwards, S., et al. *Does fatigue induced by repetitive weighted standing vertical jumps affect muscle activation patterns during landing in beach volleyball?* in *18th International Society of Biomechanics Congress*. 2001. Zurich (Switzerland): Interrepro AG, Munchenstein, Switzerland.
13. Salci, Y., et al., *Comparison of landing maneuvers between male and female college volleyball players*. Clinical Biomechanics, 2004. **19**(6): p. 622-628.
14. Brukner, P. and K.M. Khan, *Chapter 2: Sports Injuries*, in *Clinical Sports Medicine*, P. Brukner and K.M. Khan, Editors. 1993, McGraw-Hill: Sydney.
15. Garrick, J.G. and D.R. Webb, *Sports Injuries: Diagnosis and management*. 1990, Philadelphia: Saunders. xi, 347.

16. Young, M.A., et al., *Eccentric decline squat protocol offers superior results at 12 months compared with traditional eccentric protocol for patellar tendinopathy in volleyball players*. British Journal of Sports Medicine, 2005. **39**(2): p. 102-105.
17. Coleman, B.D., et al., *Open and arthroscopic patellar tenotomy for chronic patellar tendinopathy. A retrospective outcome study*. Victorian Institute of Sport Tendon Study Group. American Journal of Sports Medicine, 2000. **28**(2): p. 183-190.
18. Lian, O., et al., *Characteristics of the leg extensors in male volleyball players with jumper's knee*. American Journal of Sports Medicine, 1996. **24**(3): p. 380-385.
19. Richards, D.P., et al., *Knee joint dynamics predict patellar tendinitis in elite volleyball players*. American Journal of Sports Medicine, 1996. **24**(5): p. 676-683.
20. Martens, M., et al., *Patellar tendinitis: pathology and results of treatment*. Acta Orthopaedica Scandinavica, 1982. **53**(3): p. 445-450.
21. Blazina, M.E., et al., *Jumper's knee*. Orthopedic Clinics of North America, 1973. **4**(3): p. 665-678.
22. Richards, D.P., et al., *Relation between ankle joint dynamics and patellar tendinopathy in elite volleyball players*. Clinical Journal of Sport Medicine, 2002. **12**(5): p. 266-72.
23. Ferretti, A., P. Papandrea, and F. Conteduca, *Knee injuries in volleyball*. Sports Medicine, 1990. **10**(2): p. 132-138.
24. Roels, J., et al., *Patellar tendinitis (jumper's knee)*. American Journal of Sports Medicine, 1978. **6**(6): p. 362-368.
25. Fredberg, U. and L. Bolvig, *Jumper's knee. Review of the literature*. Scandinavian Journal of Medicine and Science in Sports, 1999. **9**(2): p. 66-73.
26. Hoffman, J.R., D. Liebermann, and A. Gusic, *Relationship of leg strength and power to ground reaction forces in both experienced and novice jump trained personnel*. Aviation Space & Environmental Medicine, 1997. **68**(8): p. 710-714.
27. Harries, M., *Oxford Textbook of Sports Medicine*. Oxford medical publications. 1994, New York: Oxford University Press. xiii, 748 , [4] of plates.
28. Johnson, D.P., C.J. Wakeley, and I. Watt, *Magnetic resonance imaging of patellar tendonitis*. Journal of Bone & Joint Surgery (British Volume), 1996. **78**(3): p. 452-457.
29. Rozzi, S.L., et al., *Knee joint laxity and neuromuscular characteristics of male and female soccer and basketball players*. American Journal of Sports Medicine, 1999. **27**(3): p. 312-319.
30. Nyland, J.A., et al., *Relationship of fatigued run and rapid stop to ground reaction forces, lower extremity kinematics, and muscle activation*. Journal of Orthopaedic and Sports Physical Therapy, 1994. **20**(3): p. 132-137.
31. Coutts, K.D., *Kinetic differences of two volleyball jumping techniques*. Medicine & Science in Sports & Exercise, 1982. **14**(1): p. 57-59.
32. Wojtys, E.M., B.B. Wylie, and L.J. Huston, *The effects of muscle fatigue on neuromuscular function and anterior tibial translation in healthy knees*. American Journal of Sports Medicine, 1996. **24**(5): p. 615-621.
33. NHMRC, *National Statement on Ethical Conduct in Research Involving Humans* 1999.
34. Cook, J.L., et al., *Patellar tendinopathy in junior basketball players: a controlled clinical and ultrasonographic study of 268 patellar tendons in players aged 14-18 years*. Scandinavian Journal of Medicine and Science in Sports, 2000. **10**(4): p. 216-220.
35. Cook, J.L., et al., *Asymptomatic hypoechoic regions on patellar tendon ultrasound: A 4-yr clinical and ultrasound followup of 46 tendons*. Scandinavian Journal of Medicine and Science in Sports, 2001. **11**: p. 321-327.
36. Cook, J.L., et al., *Prospective imaging study of asymptomatic patellar tendinopathy in elite junior basketball players*. Journal of Ultrasound in Medicine, 2000. **19**(7): p. 473-479.
37. Fredberg, U. and L. Bolvig, *Significance of ultrasonographically detected asymptomatic tendinosis in the patellar and Achilles tendons of elite soccer players: a longitudinal study*. American Journal of Sports Medicine, 2002. **30**(4): p. 488-91.
38. McLoughlin, R.F., et al., *Patellar tendinitis: MR imaging features, with suggested pathogenesis and proposed classification*. Radiology, 1995. **197**(3): p. 843-848.
39. Khan, K.M., et al., *Patellar tendinosis (jumper's knee): findings at histopathologic examination, US, and MR imaging*. Radiology, 1996. **200**(3): p. 821-827.
40. Khan, K.M., et al., *Correlation of ultrasound and magnetic resonance imaging with clinical outcome after patellar tenotomy: prospective and retrospective studies*. Victorian Institute of Sport Tendon Study Group. Clinical Journal of Sport Medicine, 1999. **9**(3): p. 129-137.
41. Black, J., et al., *Intertester reliability of sonography in patellar tendinopathy*. Journal of Ultrasound in Medicine, 2004. **23**(5): p. 671-675.
42. Lian, O., et al., *Relationship between symptoms of jumper's knee and the ultrasound characteristics of the patellar tendon among high level male volleyball players*. Scandinavian Journal of Medicine and Science in Sports, 1996. **6**(5): p. 291-296.
43. Fritschy, D. and R. de Gautard, *Jumper's knee and ultrasonography*. American Journal of Sports Medicine, 1988. **16**(6): p. 637-640.

44. Fredberg, U., et al., *Ultrasonography as a tool for diagnosis, guidance of local steroid injection and, together with pressure algometry, monitoring of the treatment of athletes with chronic jumper's knee and Achilles tendinitis: a randomized, double-blind, placebo-controlled study*. Scandinavian Journal of Rheumatology, 2004. **33**(2): p. 94-101.
45. Jonsson, P. and H. Alfredson, *Superior results with eccentric compared to concentric quadriceps training in patients with jumper's knee: a prospective randomised study*. British Journal of Sports Medicine, 2005. **39**(11): p. 847-850.
46. Cook, J.L., et al., *Patellar tendon ultrasonography in asymptomatic active athletes reveals hypoechoic regions: a study of 320 tendons*. Victorian Institute of Sport Tendon Study Group. Clinical Journal of Sport Medicine, 1998. **8**(2): p. 73-77.
47. Malliaras, P., et al., *Prospective study of change in patellar tendon abnormality on imaging and pain over a volleyball season*. British Journal of Sports Medicine, 2006. **40**(3): p. 272-274.
48. Terslev, L., et al., *Ultrasound and Power Doppler findings in jumper's knee - preliminary observations*. European Journal of Ultrasound, 2001. **13**(3): p. 183-189.
49. Gisslen, K. and H. Alfredson, *Neovascularisation and pain in jumper's knee: a prospective clinical and sonographic study in elite junior volleyball players*. British Journal of Sports Medicine, 2005. **39**(7): p. 423-428.
50. Cook, J.L., et al., *Vascularity and pain in the patellar tendon of adult jumping athletes: a 5 month longitudinal study*. British Journal of Sports Medicine, 2005. **39**(7): p. 458-461.
51. Khan, K.M., *Patellar tendon ultrasonography and jumper's knee in female basketball players: a longitudinal study*. Clinical Journal of Sport Medicine, 1997. **7**(3): p. 199-206.
52. Zatsiorsky, V., V. Seluyanov, and L. Chugunova, *In vivo body segment inertial parameters determination using a gamma-scanner method*, in *Biomechanics of human movement : applications in rehabilitation, sports and ergonomics*, N. Berme and A. Cappozzo, Editors. 1990, Bertec: Worthington, Oh. p. xi, 545.
53. Horita, T., et al., *Stretch shortening cycle fatigue: interactions among joint stiffness, reflex, and muscle mechanical performance in the drop jump*. European Journal of Applied Physiology & Occupational Physiology, 1996. **73**(5): p. 393-403.
54. Edwards, S. and J.R. Steele, *Can lower limb fatigue be reliably induced in male athletes?* Journal of Science & Medicine in Sport, 2006. **9**(6 (Supplement)): p. 45.
55. Herzog, W. and L.J. Read, *Lines of action and moment arms of the major force-carrying structures crossing the human knee joint*. Journal of Anatomy, 1993. **182**(Pt 2): p. 213-230.
56. Basmajian, J.V., D.N. Gopal, and D.N. Ghista, *Electrodiagnostic model for motor unit action potential (MUAP) generation*. American Journal of Physical Medicine, 1985. **64**(6): p. 279-294.
57. Sell, T.C., et al., *The effect of direction and reaction on the neuromuscular and biomechanical characteristics of the knee during tasks that simulate the noncontact anterior cruciate ligament injury mechanism*. American Journal of Sports Medicine, 2006. **34**(1): p. 43-54.
58. Yu, B., et al., *Immediate effects of a knee brace with a constraint to knee extension on knee kinematics and ground reaction forces in a stop-jump task*. American Journal of Sports Medicine, 2004. **32**(5): p. 1136-1143.
59. Yu, B., C. Lin, and W.E. Garrett, *Lower extremity biomechanics during the landing of a stop-jump task*. Clinical Biomechanics, 2006. **21**(3): p. 297-305.
60. Herman, D.C., et al., *The effects of strength training on the lower extremity biomechanics of female recreational athletes during a stop-jump task*. American Journal of Sports Medicine, 2008. **36**(4): p. 733-740.
61. Chappell, J.D. and O. Limpisvasti, *Effect of a Neuromuscular Training Program on the Kinetics and Kinematics of Jumping Tasks*. American Journal of Sports Medicine, 2008. **36**(6): p. 1081-1086.
62. Whitting, J.W., et al., *Parachute Landing Fall Characteristics at Three Realistic Vertical Descent Velocities*. Aviation, Space, and Environmental Medicine, 2007. **78**: p. 1135-1142.
63. Chappell, J.D., et al., *Effect of fatigue on knee kinetics and kinematics in stop-jump tasks*. American Journal of Sports Medicine, 2005. **33**(7): p. 1022-1029.
64. Horita, T., et al., *Effect of exhausting stretch-shortening cycle exercise on the time course of mechanical behaviour in the drop jump: possible role of muscle damage*. European Journal of Applied Physiology & Occupational Physiology, 1999. **79**(2): p. 160-167.
65. Cowling, E., *Does upper limb motion alter lower limb muscle coordination? Implications for ACL injury*, in *Department of Biomedical Science*. 1998, University of Wollongong: Wollongong. p. 119.
66. Steele, J.R., *Knee function of chronic ACLD patients during static knee laxity assessment and dynamic acceleration.*, in *Department of Biomedical Science*. 1997, University of Wollongong: Wollongong, New South Wales, Australia.
67. Finni, T., P.V. Komi, and V. Lepola, *In vivo human triceps surae and quadriceps femoris muscle function in a squat jump and counter movement jump*. European Journal of Applied Physiology, 2000. **83**(4-5): p. 416-426.
68. Grant, M.J., T.V. Wrigley, and G.R. Purdam. *Ground reaction forces and kinematic patterns during landings by male basketball players*. in *First Australasian Biomechanics Conference*. 1996. Sydney (Australia).
69. Edwards, S. and J.R. Steele. *Effects of fatigue on landing in Beach Volleyball*. in *4th Australasian Biomechanics Conference*. 2002. Melbourne, Australia.

70. Nicol, C., P.V. Komi, and P. Marconnet, *Fatigue effects of marathon running on neuromuscular performance I. Changes in muscle force and stiffness characteristics*. Scandinavian Journal of Medicine & Science in Sports, 1991. **1**(1): p. 10-17.
71. Madigan, M.L. and P.E. Pidcoe, *Changes in landing biomechanics during a fatiguing landing activity*. Journal of Electromyography & Kinesiology, 2003. **13**(5): p. 491-498.
72. Arendt-Nielsen, L. and T. Sinkjaer, *Quantification of human dynamic muscle fatigue by electromyography and kinematic profiles*. Journal of Electromyography and Kinesiology, 1991. **1**(1): p. 1-8.
73. Tortora, G.J. and S.R. Grabowski, *Principles of Anatomy and Physiology*. 7th ed. 1993, New York: Harper Collins College. xxvi, 999, [118].
74. Batman, P. and M. Van Capelle, *Exercise Analysis Made Simple: A step by step approach*. 1994, Northbridge, NSW, Australia: FIT4U Publications.
75. Houck, J., *Muscle activation patterns of selected lower extremity muscles during stepping and cutting tasks*. Journal of Electromyography & Kinesiology, 2003. **13**(6): p. 545-554.