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INFLUENCE OF FEMALE PUBERTAL DEVELOPMENT AND ATHLETIC FOOTWEAR ON LOWER LIMB BIOMECHANICS: IMPLICATIONS FOR NON-CONTACT ACL INJURY AND PATELLOFEMORAL PAIN

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“The person who makes a success of living is the one who sees his goal steadily and aims for it unswervingly. That is dedication.”- Bob Dylan

ABSTRACT

Adolescent girls are susceptible to knee injuries such as non-contact anterior cruciate ligament (ACL) rupture and patellofemoral pain (PFP). Adolescence is synonymous with pubertal development which drives substantial growth and maturation of the musculoskeletal system, and is thought to contribute to poor knee biomechanics associated with both of these injuries. Specifically, higher tri-planar knee moments during puberty (external peak knee abduction moment (KAbM), flexion moment (KFM) and internal rotation moment (KIRM)) are thought to contribute to a higher incidence of these injuries; however, there are still gaps in our understanding of female pubertal biomechanics. For instance, variations in dynamic tasks (i.e., bilateral vs single limb), unreliable pubertal classification methods, small sample sizes, conflicting findings and data normalisation methods (i.e., mixed between body mass or body mass by height) highlight the need for additional, better designed pubertal studies.

The role of athletic footwear is also an important consideration, given it may alter tri-planar knee moments relevant to both non-contact ACL rupture or PFP. Specifically, high-support footwear is thought to control excessive foot pronation, which may transfer up the kinetic chain and confer protection at the proximal knee joint by modifying tri-planar knee moments during dynamic tasks. By contrast, low-support shoes do not possess the same stability features, potentially allowing for greater foot pronation that may have a clinically meaningful effect on tri-planar knee moments compared to high-support shoes. Surprisingly, no studies have explored the effects of these shoes during female pubertal

development, which is concerning as many adolescent girls are likely wearing these types of shoes during the various sports in which the aforementioned knee injuries occur.

To address the current limitations in pubertal and footwear biomechanical research, four cross-sectional studies are reported in this thesis. Ninety-three girls aged between 7-25 years old were categorised into three key stages of puberty: pre-pubertal (n = 31, mean age = 9.4 ± 1.2), early/mid-pubertal (n = 31, mean age = 11.1 ± 1.4) and late/post-pubertal (n = 31, mean age = 19.8 ± 4.0). Tri-planar knee moments normalised to body mass (Nm/kg) and body mass by height (Nm/kg/m) were analysed across landing and running-related tasks in each pubertal group. These were initially observed barefoot, and then subsequently, the effect of high- and low-support footwear was explored across both tasks.

The primary aim of Study 1 was to determine whether peak tri-planar knee moments differed between three stages of female pubertal development during a barefoot single limb drop lateral jumping (DLJ) task. The secondary aim was to explore the hip adduction moment (HAM) at time of peak KAbM and the hip flexion moment (HFM) at time of peak KFM between pubertal groups. In the frontal plane, a higher peak KAbM was found for the late/post- compared to the pre-pubertal group when normalised to body mass (95%CI=-0.02 to -0.17 Nm/kg, *p*=0.015, *d*=0.61), but not body mass by height (*p*=0.88). At the hip, neither body mass or body mass by height normalised data revealed between-group differences for HAM at time of peak KAbM (*p*>0.05). In the sagittal plane, a higher peak body mass-normalised KFM was found for the late/post- (95%CI=0.19 to 0.68 Nm/kg, *p*=0.001, *d*=1.12) and the early/mid-pubertal groups compared to the pre-pubertal group (95%CI=0.05 to 0.52 Nm/kg, *p*=0.017, *d*=0.59). No significant between-group differences were found for body mass by height-normalised peak KFM (*p*=0.30) or the HFM at time of peak KFM (*p*>0.05). Finally, in the transverse plane, a higher peak KIRM in the late/post- compared to both the early/mid- (95% CI = -0.09, -0.01 Nm/kg, *p*=0.028, *d*=0.62) and pre-pubertal groups (95% CI= -0.12, -0.03 Nm/kg, *p*=0.001, *d*=0.82) was found for body mass, but not body mass by height normalised data.

The primary aim of Study 2 was to determine whether peak tri-planar knee moments differed across footwear conditions (i.e., barefoot, high-support and low-support shoes) during the single-limb DLJ amongst late/post-pubertal girls. Based on the findings in Study 1, the late/post-pubertal group was selected as they displayed higher mass normalised tri-planar knee moments compared to early/mid- and pre-pubertal counterparts and may be at higher risk of ACL injury. Results revealed no significant differences for peak KAbM or KIRM regardless of statistical adjustment for FPI (*p*>0.05). By contrast, peak KFM was higher in the high-support (95% CI= 0.36, 0.53 Nm/kg, *p*<0.001, *d*= 1.11) and low-support shoes (95% CI= 0.25, 0.48 Nm/kg, *p*<0.001, *d*= 0.85) compared to barefoot; however, no significant differences were observed between shoe conditions. Together, Study 1 and 2 provide novel insights into the effects of female puberty and footwear on the biomechanics of single-limb landing, revealing that increased pubertal-related height (i.e., stature), rather than body mass, is the main contributor to augmented tri-planar knee moments in the latter stages of female pubertal development, which athletic footwear did not ameliorate.

The primary aim of Study 3 was to examine tri-planar knee moments (normalised to body mass and body mass by height) across the three pubertal stages while running barefoot. Higher peak body mass-normalised KFM was apparent in the late/post-pubertal

(95% CI= 0.18 to 0.63 Nm/kg, *p*=0.001, *d*= 1.01) and early/mid-pubertal (95% CI= 0.02, 0.47 Nm/kg, *p*=0.034, *d*=0.52) girls compared to the pre-pubertal girls; however, no significant differences were found when KFM was normalised to body mass by height (*p*>0.05). Furthermore, no significant differences were found for body mass or body mass by height normalised peak KAbM or KIRM (*p*>0.05). At the hip, a lower body mass normalised HAM at time of peak KFM (i.e., greater hip abduction moments) was found in the late/post- (95% CI= -0.51, -0.11 Nm/kg, *p*=0.003, *d*= 0.86) and early/mid-pubertal (95% CI= -0.42, -0.01 Nm/kg, *p*=0.039, *d*= 0.53) girls compared to their pre-pubertal counterparts. Likewise, in the sagittal plane a decrease in body mass normalised HFM at time of peak KFM was evident with the late/post-pubertal girls displaying lower HFM (95% CI= 0.65, 0.28 Nm/kg, *p*<0.001, *d*=1.27) compared to their early/mid- and pre-pubertal counterparts (95% CI= 0.36, 0.73 Nm/kg, *p*<0.001, *d*=1.42).

Study 4 determined whether footwear conditions (i.e., barefoot, high-support, low-support) effect running-related peak KFM amongst a pooled sample of early/mid- and late/post-pubertal girls. Based on the findings in Study 3, girls in the early/mid- and late/post-pubertal groups were pooled as no differences in body mass normalised tri-planar knee moments were observed; however, they both displayed higher peak KFM compared to pre-pubertal girls. The secondary aim explored predictors associated with a change in the peak KFM wearing shoes compared to barefoot (i.e., knee-ground reaction force (GRF) lever arm, sagittal plane resultant GRF magnitude and sagittal plane lower limb kinematics) to help elucidate the underlying biomechanical mechanism. A main effect (*p*<0.001) for peak KFM was found, revealing both high- (95% CI= 0.36, 0.49 Nm/kg, *p*<0.001, *d*=1.07) and low-support (95% CI= 0.31, 0.45 Nm/kg, $p<0.001$, $d=0.97$) footwear increased peak KFM compared to barefoot, no differences were found between shoes ($p>0.05$). The regression models identified that only a change in the knee-GRF lever arm in shoes compared to barefoot was associated with a change in peak KFM ($F_{(1,\ 109)}= 93.56$, $p<0.001$), but not the sagittal plane GRF magnitude or any lower limb kinematics ($p>0.05$). Combined, Study 3 and 4 provide evidence for a developmental increase in sagittal plane but not frontal or transverse plane knee moments that are likely attributed to differences in adolescent height while running. More importantly, wearing shoes increased peak KFM even further regardless of whether they possessed supportive characteristics, and this was partly driven by an increase in the knee-GRF lever arm. Given the repetitive and chronic loading pattern associated with the development of adolescent PFP, both puberty and athletic footwear may influence the manifestation of this condition.

Further studies are required to prospectively determine whether higher body mass landing-related tri-planar knee moments and running-related peak KFM in the later stages of puberty are indeed linked to ACL rupture or PFP, respectively. Moreover, pubertal footwear studies may consider modifying footwear features to determine if these higher knee moments can be attenuated.

DECLARATION

This is to certify that:

i. the thesis comprises only my original work towards the PhD except where indicated in the Preface
ii. due acknowledgement has been made in the text to all other material used,
iii. the thesis is fewer than 100,000 words in length, exclusive of tables, figures, bibliographies and appendices
iv. all research procedures reported in this thesis were approved by the Human Research Ethics Committee, The University of Melbourne

AUTHOR SIGNATURE:

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PUBLICATIONS AND CONFERENCE PAPERS

The following publications and conference presentations were developed by work related to this thesis:

Under peer-review

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Sayer TA, Hinman RS, Paterson KL, Fortin K, Bennell KL, Timmi A, Pivonka P, Bryant A. Effect of footwear on tri-planar knee moments during single limb landing: part 2. 23/11/17 *Eur J Sport Sci***.** (Study 2, Chapter 4)

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Conference presentations

Sayer TA, Hinman RS, Paterson KL, Fortin K, Bennell KL, Timmi A, Pivonka P, Bryant A. Female pubertal development increases aberrant non-dominant knee biomechanics: implications for non-contact anterior cruciate ligament injury. Paper presented at the 2017 Sports Medicine New Zealand conference, Auckland, NZ.

Sayer TA, Paterson KL, Fortin K, Hinman RS, Bennell KL, Timmi A, Pivonka P & Bryant AL. Inter-limb differences during single and bilateral landing in girls: implications for appropriately identifying ACL risk factors. Paper presented at the 2017 Sports Medicine Australia conference. Melbourne, Australia.

AWARDS

1. National Health and Medical Research Council (NHMRC) Postgraduate Scholarship
2. 2nd place best speaker at the School of Health Sciences Colloquium, The University of Melbourne

ABBREVIATIONS

2-D	2-dimensional
3-D	3-dimensional
ACL	anterior cruciate ligament
ACLR	anterior cruciate ligament reconstruction
AJC	ankle joint centre
ANCOVA	analysis of covariance
ANOVA	analysis of variance
ARC	Australian research council
BD	breast development
BH	body height
BMI	body mass index
BW	bodyweight
C3D	co-ordinate 3-dimensional
CHESM	centre for health exercise and sports medicine
CI	confidence interval
CNS	central nervous system
DLJ	drop lateral jump

DVJ	drop vertical jump
EMG	electromyography
FAT	footwear assessment tool
FPI	foot posture index
FSH	follicle stimulating hormone
GRF	ground reaction force
HAM	hip adduction moment
HEAG	human ethics advisory group
HESC	human ethics sub committee
HFM	hip flexion moment
HJC	hip joint centre
HPGA	hypothalamic pituitary gonadal axis
ICC	intraclass correlation coefficient
KAbM	knee abduction moment
KFM	knee flexion moment
KJC	knee joint centre
kg	kilograms
KIRM	knee internal rotation moment
LH	landing height

LH	luteinizing hormone
LPI	lateral preference inventory
LSD	least significant difference
MD	mean difference
MRI	magnetic resonance imaging
mRNA	messenger ribonucleic acid
Nm	Newton metre
OCP	oral contraceptive pill
PFJ	patellofemoral joint
PFP	patellofemoral pain
PHV	peak height velocity
PMOS	pubertal maturation observational scale
SD	standard deviation
SPSS	statistical packages for social sciences

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CHAPTER 1

INTRODUCTION AND THESIS OVERVIEW

1.1 OVERVIEW OF THESIS

The studies in this thesis were conducted at the Centre for Health, Exercise and Sports Medicine (CHESM) movement laboratory at the University of Melbourne between March 2014 and August 2017. The overall aim of the research was to investigate whether tri-planar knee moments associated with non-contact anterior cruciate ligament (ACL) injury and the development of patellofemoral pain (PFP) were different across the three key stages of female pubertal development (pre-, early/mid- and late/post-puberty). Furthermore, the effect of athletic footwear (high- and low-support) was explored to determine whether these shoes have the capacity to alter knee loads and, as such, have potential benefits for the prevention of adolescent knee injuries.

To achieve these aims, four separate cross-sectional studies were conducted involving ninety-three healthy physically active girls from ages 7-25 years. Valid and reliable methods for pubertal classification were utilized. A novel single-limb landing task relevant to non-contact ACL biomechanics was developed and a running task was incorporated to investigate PFP-related biomechanics. Criteria for the classification of high- and low-supportive footwear were included. The data analysis procedures described in this thesis were developed specifically for the research and built upon the methodology of previous studies. An overview of the structure of the thesis is as follows:

Chapter one is an overview of the thesis and introduction to the problem.

Chapter two is a review of the literature pertaining to knee and hip biomechanics during puberty, with reference to both non-contact ACL injury and PFP. Furthermore, a discussion of current footwear and/or foot-based intervention studies are presented with respect to both landing and running tasks. The findings of this literature review were used to inform the four cross-sectional observational studies that comprise the research undertaken for this thesis (Chapter 3-6).

Chapter three is the first of four cross-sectional studies included in this thesis. In this study, single-limb landing-related hip and knee moments are examined between the three stages of female pubertal development while barefoot to establish an understanding of normal landing–related developmental biomechanics.

Chapter four describes the effect of footwear conditions (i.e., high-support, low-support and barefoot) on tri-planar knee moments in the late/post-pubertal group, based on the findings from chapter three.

Chapter five investigates the barefoot running-related differences in knee and hip moments between the three pubertal stages to clarify normal developmental-related running biomechanics.

Chapter six investigates the effect of footwear conditions (i.e., high-support, low-support and barefoot) on the peak sagittal plane knee moment and explores the underlying mechanism for differences between footwear conditions.

Chapter seven summarizes the findings of the four studies and presents the strengths and limitations of this thesis. Finally, future directions are outlined based on the findings presented in this thesis.

1.2. INTRODUCTION

Puberty is a crucial period in human development, with numerous systems maturing for adulthood (Moshang 2005). Generally, puberty is defined as the period in which an individual is capable of reproduction; however, several other important cellular and systemic processes occur during this timeframe (Tanner et al. 1976, Faust 1977, Styne 2003). These may ultimately play a role in the higher incidence of adolescent musculoskeletal injury (Arendt et al. 1999, Powell and Barber-Foss 2000, Shea et al. 2004).

Indeed, there is evidence that musculoskeletal injuries increase across pubertal stages (Michaud et al. 2001); however, there is currently no published data classifying type of injuries across pubertal stages. Instead, injury surveillance data has categorised adolescent females by chronological age (Arendt et al. 1999, Powell and Barber-Foss 2000, Shea et al. 2004). It appears that as girls transition through adolescence towards adulthood - a period where individuals would be expected to transition from pre- to post-pubertal development - an increase in the prevalence of both traumatic and overuse knee injuries are reported. Specifically, traumatic knee injuries such as non-contact anterior cruciate ligament (ACL) rupture is approximately 4-fold higher during early/mid- adolescence (i.e., approximately early/mid -pubertal stages) compared to childhood (i.e., pre-pubertal stages) (Arendt et al. 1999, Powell and Barber-Foss 2000, Shea et al. 2004). Likewise, overuse type injuries such as patellofemoral pain (PFP) are approximately 15-30% higher in adolescent girls aged 13-17 years compared to younger girls (Fairbank et al. 1984, Myer et al. 2010).

Regarding traumatic non-contact ACL injury, many individuals in Australia undergo ACL reconstructive (ACLR) surgery in order to restore mechanical stability of the knee (approximately 50, 000 surgeries annually; (Janssen et al. 2012)). Importantly, many of these ACLR's are performed during early-late adolescence, which is concerning given that ACL graft rupture following ACLR is high (Paterno et al. 2010, Paterno et al. 2015) and many ACLR patients develop early-onset knee osteoarthritis in the subsequent 10-15 years (Lohmander et al. 2007, Frobell 2011, Maerz et al. 2016). Similarly, PFP can have an adverse effect on girls participation in sport and recreational exercise due to the recurrent and diffuse presentation of retropatella pain (Fairbank et al. 1984) and, similar to ACL injury, can lead to patellofemoral osteoarthritis in later life (Wyndow et al. 2016). Given that sport and exercise is encouraged from a young age to prevent systemic health problems such as obesity, diabetes and cardiovascular disease (Garcia-Hermoso et al. 2016, Ruiz et al. 2016), it is critical that strategies are employed to prevent these types of knee injuries.

While prevention of adolescent knee injuries through neuromuscular training programs is currently endorsed by many researchers and clinicians (Emery et al. 2015), the complex and multi-factorial aetiology of non-contact ACL rupture and PFP makes it challenging to design effective preventative interventions. For instance, traumatic non-contact ACL injury in females has been attributed to altered anatomical alignment (Nguyen and Shultz 2007, Schmitz et al. 2009), muscle strength (Quatman-Yates et al. 2013), hormonal fluctuations (Wild et al. 2012, Wild et al. 2013) and lower limb biomechanics (Hewett et al. 2004, Hass et al. 2005, Hewett et al. 2006, Ford et al. 2010, Sigward et al. 2012, Wild et al. 2013, Kim and Lim 2014, Wild et al. 2016). Similarly, PFP has also been reported to manifest due to altered lower limb biomechanics (Brechter and Powers 2002, Powers 2003, Chen and Powers 2014), anatomical alignment (Messier et al. 1991, Thomee et al. 1999), muscle strength (Pappas and Wong-Tom 2012, Almeida et al. 2016, Van Cant et al. 2017), neuromuscular recruitment patterns (Thomee et al. 1999, Cowan et al. 2009) and hormonal fluctuations (Hewett 2000).

However, given that several of these factors are non-modifiable (i.e., genetics, anatomical alignment, hormonal fluctuations), a large proportion of research has focussed on the characterisation of modifiable factors such as altered lower limb biomechanics (Hewett et al. 2004, Hass et al. 2005, Hewett et al. 2006, Ford et al. 2010, Sigward et al. 2012, Wild et al. 2013, Kim and Lim 2014, Wild et al. 2016). With respect to female pubertal non-contact ACL injury, these studies have predominantly reported a higher external knee abduction moment (KAbM) in girls at the latter stages of puberty (Ford et al. 2010, Sigward et al. 2012, Kim and Lim 2014). Subsequent prospective studies involving adolescent females have linked higher peak KAbM with non-contact ACL rupture (Hewett et al. 2005) given that this moment is argued to rotate the knee into dynamic valgus, increasing ACL strain and injury risk (Hewett 2000).

Although peak KAbM is an important variable related to non-contact ACL injury during puberty, it is also important to consider the sagittal and transverse planes given that evidence suggests that ACL injury is more likely to occur via tri-planar loading (Quatman et al. 2010). Specifically, the peak sagittal plane knee flexion moment (KFM) and transverse plane knee internal rotation moment (KIRM) should be considered in female pubescent cohorts (Quatman et al. 2010) as combined knee loads (i.e., higher knee abduction and rotation) dramatically increase ACL strain compared to knee abduction alone (Shin et al. 2011).

While greater tri-planar knee moments are important contributors to ACL injury, there is currently a lack of studies reporting all three knee moments across key pubertal stages (i.e., pre-, early/mid, late/post-puberty) of adolescent females. Rather, the majority of studies have reported either uni- or bi-planar knee moments with non-concordant findings (Hass et al. 2003, Hass et al. 2005, Sigward et al. 2012, Kim and Lim 2014), which is probably partly attributed to between-study variations in landing tasks (i.e., single vs bilateral) (Hewett et al. 2004, Hass et al. 2005, Hewett et al. 2006, Ford et al. 2010, Sigward et al. 2012, Wild et al. 2013, Kim and Lim 2014, Wild et al. 2016). Quite surprisingly, many of the aforementioned pubertal biomechanical studies relevant to non-contact ACL rupture have utilised a bilateral drop vertical jump (DVJ) task (Hewett et al. 2004, Hewett et al. 2006, Ford et al. 2010, Sigward et al. 2012); however, the bilateral DVJ was recently found to be a poor screening tool for ACL injury (Krosshaug et al. 2016). In contrast, single-limb landing tasks may be more appropriate for characterising pubertal knee moments relevant to non-contact ACL injury, given this more accurately reflects the movement in which the injury occurs. Despite this, few studies to date have incorporated single-limb landing tasks and these have conflicting findings (Hass et al. 2003, Hass et al. 2005, Kim and Lim 2014) likely because these studies have used unreliable pubertal classification methods (Hass et al. 2003, Hass et al. 2005, Kim and Lim 2014). Hence, additional single-limb landing studies incorporating more rigorous classification of pubescent participants are required to elucidate whether tri-planar knee moments differ according to female pubertal stage.

Increased running-related tri-planar knee moments are also suggested to play a role in the manifestation of PFP in adolescent females. Higher peak KFM has been linked with higher patellofemoral joint (PFJ) stress (van Eijden et al. 1986, Bonacci et al. 2014) and has been shown to contribute to patellofemoral cartilage degradation (Teng et al. 2015), which may exacerbate PFJ symptoms. Similarly, elevated landing-related peak KAbM amongst adolescent females has been associated with the development of PFP. (Myer et al. 2014) While there is currently no evidence pertaining to the role of peak KIRM, higher knee internal rotation angles increase PFJ cartilage stress in symptomatic PFP individuals, thereby suggesting it may also be an important variable associated with adolescent female PFP (Liao et al. 2015). Although increased tri-planar knee moments during running are suspected to contribute to the development of PFP (van Gent et al. 2007), currently there are no biomechanical studies investigating the effect of female pubertal development on tri-planar knee moments during running. Understanding whether these knee moments are different between developmental stages of adolescent females is important, as it may provide insight into why the rates of PFP increase throughout adolescence.

Despite the aforementioned limitations of studies examining pubertal knee biomechanics associated with both non-contact ACL injury and PFP, research into strategies which may ameliorate augmented tri-planar knee moments during landing and running-related tasks are also required. Current strategies include neuromuscular training interventions that focus on plyometric drills, stretching and strength training, and these have been reported to have a positive effect on reducing the risk of knee injuries amongst young athletic females (Hewett 2000, Neal et al. 2016). However, concerns regarding implementation and effectiveness of such programs have been raised, as they are time-consuming, require expert instruction and are hampered by poor participant compliance (Grimm et al. 2013). Therefore, alternative conservative strategies, such as athletic footwear that are cost effective, user-friendly and easy to implement at a population level, may modify knee loads to ultimately reduce female adolescent knee injuries.

Specifically, high-supportive footwear includes characteristics such as increased medial arch support, longitudinal shoe stiffness and midfoot rotational stability. These may reduce excessive foot pronation, and in turn, might influence the biomechanics of the more proximal segments in the kinetic chain and attenuate peak KAbM and KIRM (Williams et al. 2003, Franz et al. 2008, Joseph et al. 2008, Eslami et al. 2009, Jenkins et al. 2009). However, shoes may also increase peak KFM given the associated increase in ankle dorsiflexion attributed to the increased heel height in these shoes (Sinclair 2014). Because many adolescent females will typically wear a mixture of footwear styles designated as either high- or low-support during sports associated with acute and chronic knee injury, it is important to characterise footwear-related biomechanical effects amongst a pubertal developmental cohort to determine whether footwear is efficacious in reducing potentially injurious knee loads.

In light of these considerations, the primary aim of this thesis was to determine the effect of pubertal development (i.e., pre-, early/mid- and late/post-puberty) on tri-planar knee moments during single-limb landing and running whilst barefoot. The secondary aim was to examine the biomechanical effects of athletic footwear (i.e., high-support, low-support and barefoot) on tri-planar knee moments of pubescent females.

CHAPTER 2

LITERATURE REVIEW

2.1. CHAPTER OVERVIEW

Lower limb biomechanics related to non-contact ACL injury and PFP have been widely studied. With respect to gender, a plethora of studies have reported higher peak knee moments in females compared to their male counterparts (Csintalan et al. 2002, Swartz et al. 2005, Hewett et al. 2006, Schmitz et al. 2009, Boling et al. 2010, Ford et al. 2010, Sigward et al. 2012, DiStefano et al. 2015), suggesting that these differences may partly explain the disproportionately higher rates of female ACL injury (Arendt et al. 1999, Powell and Barber-Foss 2000) and PFP (Fairbank et al. 1984, Myer et al. 2010). More recently, it has been suggested that female pubertal development may play a role in the manifestation of abnormal knee biomechanics that contribute to both ACL rupture and PFP (Hewett et al. 2004, Myer et al. 2014, Hewett et al. 2016); however, further research is required.

Currently, it is unclear whether knee biomechanics during jumping and running tasks differ between girls at different stages of female pubertal development. This information is pivotal to our understanding of biomechanical factors contributing to adolescent female non-contact ACL rupture and PFP and the subsequent design of injury prevention interventions. In this respect, no studies to date have investigated the effect of commercially available high- and low- supportive footwear on tri-planar knee moments during female pubertal development. Given that many girls will typically wear a mixture of high- and low-supportive footwear as they transition through adolescence (i.e., puberty), in combination with a higher rate of knee injury (Fairbank et al. 1984, Powell and Barber-Foss 2000, Myer et al. 2010), understanding whether different shoes alter biomechanics associated with these injuries is important. Therefore, this literature review will critically appraise research related to the four studies presented in this thesis and is organised into the following sections:

2.2. Characteristics of puberty

2.3. Pubertal stage classification in females

2.4. Knee injuries across the Tanner stages

2.5. Knee biomechanics associated with pubertal non-contact ACL injury

2.6. Mechanisms underlying adolescent PFP development

2.7. The role of athletic footwear

2.8. Summary

2.2. CHARACTERISTICS OF PUBERTY

Puberty is a crucial systemic process and is the physiological transition from childhood to adulthood. In females, sex hormones (i.e., estrogen, progesterone and testosterone) are responsible for a range of physical changes associated with female pubertal development (Moshang 2005). For the purposes of this thesis, only growth in relation to long bones, menarche and the maturation of breast tissue is discussed, as other processes are outside the scope of this thesis.

2.2.1. PHYSIOLOGICAL CONTROL OF SKELETAL GROWTH, BREAST TISSUE FORMATION AND MENARCHE

The central nervous system (CNS) (Styne 2003) initiates pubertal development via the hypothalamic pituitary gonadal axis (HPGA). The HPGA is a negative feedback pathway that drives development of secondary sex characteristics via production of sex hormones. As these hormones gradually rise in the pre-pubescent phase, they reach concentrations high enough to stimulate skeletal growth (i.e. long bone growth) and breast tissue formation (Beardwood and Russell 1970, Faiman et al. 1976, Moshang 2005).

Long bone growth primarily occurs at the growth plate, whereby sex and growth hormones regulate bone formation and resorption, ultimately leading to bone elongation (Moshang 2005). The majority of this process occurs rapidly throughout puberty, typically referred to as the peak height velocity (PHV) or adolescent growth spurt (see Section 2.3.1, (Tanner et al. 1976). Towards the end of puberty, estrogen acts on cells within the chondroplasia zone (i.e., chondrocytes), where the hormone is thought to arrest bone elongation, inducing growth plate fusion (Moshang 2005).

In addition to regulation of long bone growth, hormones also play a critical role in breast tissue development. In the pre-pubertal phase, the immature human breast is arranged into a small network of ducts and fat pads (Kleinberg and Ruan 2008). Essentially, breast tissue formation begins in these small ducts, in which growth hormones within the mammary stromal cells stimulate the mammary terminal end bud (Kleinberg and Ruan 2008, Eccles 2011). Consequently, this process leads to proliferation of the immature ducts and invasion of the fat pad - a process known as ductal morphogenesis (Kleinberg and Ruan 2008, Eccles 2011). Together growth hormones and estradiol (the most common form of estrogen) contribute to breast tissue formation throughout puberty, until additional growth factors stimulate epithelial cell proliferation and finalise maturation of the mammary epithelium towards the end of puberty (Stull et al. 2002).

Higher estrogen levels during puberty also stimulate progressive maturation of the female reproductive system, eventually leading to menarche, otherwise known as the onset of the first menstrual cycle (Golub 1983). The physiological regulation of menarche is primarily controlled by the HPGA, whereby the combination of estrogen, follicle stimulating hormone and luteinizing hormone cause growth of the ovarian follicle and endometrium, eventually leading to menstruation during early adolescence (Golub 1983). Together with long bone growth and breast tissue formation, these three characteristics of female pubertal development are important when classifying girls into stages of puberty, a topic discussed in the following section.

2.3. PUBERTAL STAGE CLASSIFICATION IN FEMALES

Classification of female pubertal stage is vital to determine the degree of biological development. A detailed review by Wild and colleagues (2012) outlined several pubertal classification techniques (Wild et al. 2012). The authors concluded that chronological age, self-determined scales of breast development (i.e., Tanner stages), skeletal age, the adolescent growth spurt and menarche are all efficacious in the classification of pubertal development. However, many of these classification techniques have limitations as primary determinants of pubertal phase (i.e., pre-, early/mid-, late/post-puberty) (Wild et al. 2012). For instance, chronological age and menarche can be highly variable (Tanner et al. 1976, Faust 1977, Wild et al. 2012), assessment of skeletal age is expensive and requires exposure to radiation (Tanner et al. 1976, Dvorak et al. 2007, Wild et al. 2012), while quantifying time from the adolescent growth spurt is time consuming and physical measurements of breast development as per the Tanner stages can be embarrassing (Tanner et al. 1976, Faust 1977, Wild et al. 2012). Despite these limitations, the adolescent growth spurt and menarche together with the Tanner stages are still commonly utilised measures and, in combination, can provide an appropriate level of pubertal stage classification. These are described in the following sections.

2.3.1. PEAK HEIGHT VELOCITY AND MENARCHE

The measurement of long bone growth (i.e., increased height) in puberty was first described by Tanner in 1976 (Tanner et al. 1976). This was an important study that identified the rapid growth in height during adolescence, referred to as the adolescent growth spurt or peak height velocity (PHV) (Tanner et al. 1976, Tanner 1986). Subsequently defined as the stage when height '*averages 10.5 cm a year in boys and 9cm per year in girls*' (Tanner 1986), PHV is commonly used in studies as part of pubertal classification (Davies and Rose 2000, Ford et al. 2010 A, Sigward et al. 2012). It is important to note that this average height increases gradually from the time of pubertal onset and reaches maximum velocity at approximately 12 years old in girls (Tanner 1986). However, given environmental, nutritional and social circumstances, this average height increase can vary among different populations (Tanner 1986).

Unfortunately, there are currently no studies reporting the reliability and validity of the PHV as a primary measure of pubertal stage. Instead, PHV is normally used as secondary characteristic within other pubertal scales such as the pubertal maturation observational scale (PMOS) as it is normally a characteristic of girls somewhere within the early-late pubertal stages (Davies and Rose 2000). In this context, the PHV should not be used a primary indicator of pubertal stage, rather it should be used alongside more reliable and valid methods.

The presence of menarche has also been used as a guide for pubertal stage (Hass et al. 2005, Wild et al. 2012, Kim and Lim 2014). As mentioned in Section 2.2.1, menarche is the onset of the first menstrual cycle, typically noted by the presence of menstrual bleeding

(Dambhare et al. 2012, Wild et al. 2012, Dorn et al. 2013). Given that the onset of the menstrual cycle accompanies higher levels of estrogen during puberty (Wild et al. 2012), menarche has the potential to discriminate whether girls have begun pubertal-development.

However, no studies have reported the validity of menarche compared to the 'gold-standard' of physician examination or other valid pubertal assessments (e.g. PMOS). Furthermore, a lack of reliability studies pertaining to menarche is also evident. Despite the lack of reliability and validity, a noteworthy study by Dorn and colleagues (2013) highlights the clear variation in age at menarche. Specifically, 253 girls across an age range of 11-17 years old demonstrated a large (approximately 2.3 years) variation in age at menarche, with up to 9% of the cohort >4.5 years apart (Dorn et al. 2013). Additionally, Dambhare et al. (2012) reported that approximately 56% of girls aged between 10-19 years old in their study (n=1100) experienced dysmenorrhea and premenstrual syndrome symptoms (Dambhare et al. 2012). Clearly, due to variations in age at menarche and the lack of clinometric studies supporting its use as a primary determinant of pubertal stage, menarche is better used as a complimentary characteristic alongside more appropriate developmental scales such as the Tanner stages.

2.3.2. TANNER STAGES OF BREAST DEVELOPMENT

The Tanner stages are one of the most commonly used developmental classification systems for characterising females into pubertal stages (Tanner et al. 1976, Tanner 1986). Whilst determination of Tanner stage can be embarrassing for young adolescents (Wild et al. 2012), this can be overcome by altering the delivery method (i.e. online or private selfrating) (Tanner et al. 1976, Tanner 1986, Brooks-Gunn et al. 1987, Chan et al. 2008, Pereira et al. 2014, Rasmussen et al. 2015). Typically, illustrations and descriptions are used to characterise an individual's pubertal stage via a 5 point likert-type scale where 1 represents the pre-pubescent stage and 5 the adult/mature stage (see Figure 2.1(Tanner et al. 1976, Tanner 1986). A discussion of the clinometric properties of the Tanner stages of breast development is provided in the following sections.

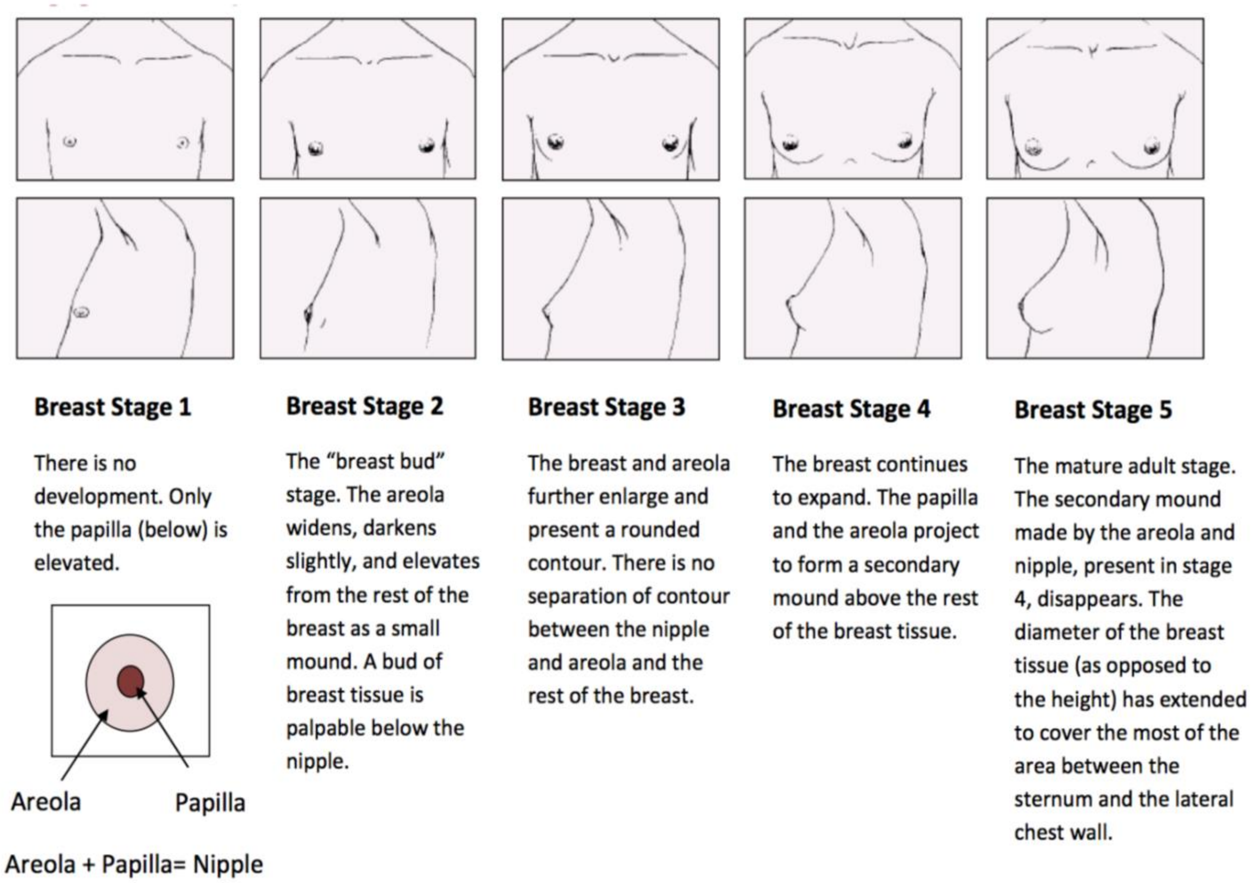
2.3.3. CLINOMETRIC PROPERTIES OF THE TANNER STAGES

2.3.3.1. VALIDITY

In quantifying the validity of the Tanner stages (see Table 2.1), the 'gold standard' is typically clinical examination by an expert physician who classifies individuals as either pre-, mid- or post-pubertal development (Leone and Comtois 2007, Pereira et al. 2014, Rasmussen et al. 2015, Fugl et al. 2016). Recently, Fugl and colleagues (2016) conducted the most sophisticated validity study to date, in which Tanner stage of breast development was determined by a physician on clinical examination and was rated against magnetic resonance imaging (MRI) for glandular breast tissue development. They found a significant positive correlation (r=0.85) between glandular breast tissue formation via MRI and the Tanner stage classification performed by the physician (Fugl et al. 2016). It was suggested that the physician-determined Tanner stages provided high sensitivity and specificity of 95% and 96% respectively.

In support of these findings, Rasmussen et al. (2015) compared 418 girls and 550 parent's classification of breast stages to physical examination by a qualified physician and found that 90.2% of girls and 86.2% of parents were correct in their assessment. In addition, the authors reported that 92.4% of girls correctly identified the pre-pubertal stage (i.e. Tanner stage 1) and 84.3% of parents correctly determined their daughter's pubertal onset (i.e. Tanner stage 2). However, breast stages appear to have poor-fair validity when ratings were analysed relative to exact Tanner stages, with only 44.9% of girls correctly identifying their breast stage of development (Rasmussen et al. 2015).

Whilst Rasmussen et al. (2015) reported mixed findings, Pereira et al. (2014) examined whether girls and their mothers could detect the breast bud development stage (i.e., onset of puberty which corresponds with Tanner stage 2) compared to a clinical examination by a trained nutritionist. Agreement between girls and the nutritionist rater was very poor ($\kappa<0.1$); however, mothers were significantly better (i.e., $\kappa=0.7$), indicating a moderate level agreement with the nutritionist. Combined, these studies highlight the notion that the Tanner stages of breast development provide a valid characterisation of distinct pubertal phases (i.e., pre, early/mid and late/post-puberty), but are limited at identifying exact stage of breast development.



Breast Stage 1

There is no development. Only the papilla (below) is elevated.

Breast Stage 2

The "breast bud" stage. The areola widens, darkens slightly, and elevates from the rest of the breast as a small mound. A bud of breast tissue is palpable below the nipple.

Breast Stage 3

The breast and areola further enlarge and present a rounded contour. There is no separation of contour between the nipple and areola and the rest of the breast.

Breast Stage 4

The breast continues to expand. The papilla and the areola project to form a secondary mound above the rest of the breast tissue.

Breast Stage 5

The mature adult stage. The secondary mound made by the areola and nipple, present in stage 4, disappears. The diameter of the breast tissue (as opposed to the height) has extended to cover the most of the area between the sternum and the lateral chest wall.

Figure 2.1. Modified Tanner stage of breast development. A 5 stage likert-type scale exists for the Tanner stages of breast development progressing from stage 1 (pre-pubertal) to 5 (post-pubertal). Descriptions accompany the diagram to aid participants selecting the relevant stage. Figure adapted from Tanner, 1986 (Tanner 1986).

Table 2.1. Validity of Tanner stages of breast development. Each study is arranged according to the participants included, broad methods that include statistics utilised, type of Tanner stage diagrams provided to participants. Only results pertaining to females is presented. Any study which also included males was ignored as it wasn't relevant for this thesis.

Study	Participants	Methods	Tanner stage type	Results	Summary
Pereira et al. (2014)	481 girls (mean age 7.8 ± 0.4)	Onset of breast development (Tanner stage 2) via clinical examination by trained nutritionist vs mother and daughter ratings Weighted kappa (κ)	Photographs	Girls vs trained nutritionist κ <0.1 Mother's vs trained nutritionist κ=0.7	Mother's have far greater validity at detecting the onset of breast development compared to their daughter's
Rasmussen et al. (2015)	418 girls (mean age 10.9)* and 550 parents	Physician clinical examination via Tanner stages compared to girls and their parent's ratings Weighted kappa (κ), sensitivity and specificity	Line drawings with additional worded descriptions	90.2% of girls and 86.2% of parents correctly identified puberty Girls vs physician exact pubertal stage ratings κ =0.28, sensitivity = 0.88, specificity = 0.92 Parent vs physician exact pubertal stage κ=0.28, sensitivity = 0.86 , specificity = 0.61	Both girls and their parents demonstrate high validity for identifying they have commenced puberty. However, poor validity for correctly identifying exact pubertal stage compared to physician
Fugle et al. (2016)	100 girls (9.8-14.7 years old)**	Physician clinical examination via Tanner stages and 3-T MRI (Magnetom Verio; Siemens AG, Germany) images of glandular breast tissue	unable to determine	MRI and physician rated Tanner stages correlation $r = 0.858$ Sensitivity = 96% and specificity = 95% for Tanner stage rating via physician examination compared to MRI	MRI derived breast tissue formation is highly correlated with Tanner stage classification via physician clinical examination

** unable to determine mean age

* unable to get standard deviation

2.3.3.2. RELIABILITY

Numerous studies have investigated inter-rater reliability of Tanner stage assessment through a combination of self-determined or parental-determined classifications (see Table 2.2).

A study by Chan et al. (2008) included girls aged 8-18 years from Hong Kong who were required to self-rate their breast stage of development (Chan et al. 2008). Analysis of inter-rater reliability revealed that 56% of girls exhibited complete agreement with an adult rater familiar with the Tanner stages, with a moderate overall inter-rater correlation (i.e., 0.72) (Chan et al. 2008). Similar levels of agreement between girls and raters have been reported in other studies (Duke et al. 1980, Morris and Udry 1980, Neinstein 1982, Wacharasindhu et al. 2002, Leone and Comtois 2007). In contrast, a large cohort study by Jaruratanasirikul and colleagues (2015) included 927 girls and reported an inter-rater agreement of 0.50 (Jaruratanasirikul et al. 2015). Likewise, Taylor et al. (2001) found poor inter-rater agreement ($\kappa = 0.43$) between a physician and 43 girls who had a mean age of 14.7 ± 1.3 years old.

Clearly, there is considerable variation in reported inter-rater reliability values of breast development; hence, use of the Tanner stages as a reliable tool for pubertal assessment appears questionable. However, there are some reasons for conflicting findings. Firstly, allowing young girls to self-determine their stage of development is a major methodological flaw, as these girls may not understand the subtle differences between pubertal stages, regardless of how much information is provided. This was highlighted by Brooks-Gunn et al. (1987) who demonstrated strong agreement between raters when mothers performed the ratings instead of their daughters (Brooks-Gunn et al. 1987). Secondly, drawings depicting Tanner stages appear mixed and inconsistent across studies. For instance, poor quality line drawings decreased the correlation between raters (Morris and Udry 1980, Jaruratanasirikul et al. 2015, Rasmussen et al. 2015), whereas better quality images with accompanying descriptive text improves reliability (Duke et al. 1980, Neinstein 1982).

In summary, the Tanner stages of breast development provide a good level of reliability and validity for broad categorisation of female pubertal stage. However, in order to optimise reliability and validity, girls <12 years old should be accompanied by a parent when rating their development and scales should provide sufficient information (i.e., text descriptions and good quality illustrations) to allow appropriate categorisation.

Table 2.2. Inter-rater reliability of Tanner stages of breast development. Each study is arranged according to the participants included, broad methods that include statistics utilised, type of Tanner stage diagrams provided to participants. Only results pertaining to females is presented. Any study which also included males was ignored as it wasn't relevant for this thesis.

Study	Participants	Methods	Tanner stage type	Results	Summary
Chan et al. (2008)	182 girls mean age 12.4 ± 1.8	Inter-rater reliability between Trained adult vs girls self-selected rating κ coefficient reported	Line drawings	Agreement between self-selected and trained adult rater was strong ($\kappa = 0.72$)	The Tanner stages of breast development provide an appropriate level of inter-rater reliability with higher levels offered with the use of parental guidance
Jaruratanasirikul et al. (2015)	927 girls mean age 11.5 ± 2.5	Inter-rater reliability between physician rating and girls self-selected stage κ coefficient reported	Line drawings	Agreement between physician and girls was poor-moderate (κ=0.50)	
Leone et al. (2007)	23 girls mean age 14.9 ± 1.6	Inter-rater reliability between physician and girls self-selected stage κ coefficient reported	Line drawings with additional worded descriptions	Agreement between physician and girls was strong (κ=0.85)	
Brooks-Gunn et al. (1987)	151 girls Mean age 12.2 ± 0.8*	Inter-rater reliability between trained nurse, participant and mothers Pearson coefficient (r) reported	Line drawings	Agreement between girls and trained nurse was strong (r=0.72) Agreement between mother's and nurse was stronger than girls (r=0.80)	
Morris & Udry (1980)	47 girls mean age 13.5 ± 1.3*	Inter-rater reliability between pediatrician and girls self-selected stage Pearson coefficient (r) reported	Line drawings with descriptive text	Agreement between pediatrician ratings and girls was moderate (r= 0.63)	

Duke et al. (1980)	43 girls aged 9-17**	Inter-rater reliability between physician and girls self-selected stages Pearson coefficient (*r*) reported	Photographs with descriptive text	Agreement between physician and girls was strong ($r = 0.81$)	
Neinstein, L.S. (1982)	22 girls aged 11-18**	Physician rating vs self-selected rating Pearson coefficient (*r*) reported	Photographs with descriptive text	Agreement between physician and girls was strong ($r = 0.87$)	
Wacharasindhu et al. (2002)	100 girls aged 7-15 **	Inter-rater reliability between pediatrician and girls self-selected rating κ coefficient reported	Photographs with descriptive text	Agreement between pediatrician and girls was strong ($\kappa = 0.76$)	
Taylor et al. (2001)	41 girls mean age 14.7 ± 1.3	Inter-rater reliability between physician and girls self-selected stages κ coefficient reported	Line drawings with description	Agreement between physician and girls was poor ($\kappa = 0.43$)	
Wu et al. (2001)	621 girls mean age 13.1 ± 0.7*	Inter-rater reliability between registered nurse and girls self-selected stages Comparison made between races Three annual ratings were performed Modified Tanner stage to detect areola κ coefficient reported	Line drawings	Agreement between nurse and girls was poor-moderate across race ($\kappa = 0.32$-0.51)	

* designates estimated calculation of mean age from study

** unable to determine mean age

2.4. KNEE INJURIES ACROSS THE TANNER STAGES

The association between the Tanner stages of pubertal development and musculoskeletal injury rates was investigated by Michaud et al. (2001, Figure 2.2). Transition from Tanner stage 1 to 5 resulted in higher injury rates, with a ~10% increase in musculoskeletal injuries from Tanner stage 1 (i.e., pre-pubertal) compared to Tanner stage 4/5 (i.e., late/post-pubertal, (Michaud et al. 2001). Although these findings highlight a link between female pubertal development and musculoskeletal injury, there is currently no evidence discriminating the prevalence of specific joint injury by pubertal stage.

The best approximation of injury-related literature relevant to pubertal development is chronological age. In this respect, girls aged 10-17 years have a higher incidence of musculoskeletal injury compared to girls aged 5-9 years (Henschke et al. 2014). Interestingly, during the transition from childhood to adulthood, ACL injury increases from 6.3% to 10.6% and PFP from 7.6% to 10.3% (Stracciolini et al. 2013). Similarly, Powell and Barber-Foss (2000) collected injury data from high school students participating in baseball, softball, basketball and soccer and found that ~10.8-19.4% of girls incurred a knee injury (Powell and Barber-Foss 2000).

Regarding the type of knee injury, Shea et al. (2004) compiled a comprehensive analysis of 8215 musculoskeletal injury insurance claims, in which 22% of all injuries occurred at the knee and 31% of these were ACL ruptures (Shea et al. 2004). Moreover, when knee injury data were separated by gender and age, of all knee injuries experienced by girls aged between 5-18 years, 37% were ACL ruptures compared to 24% in boys (Shea et al. 2004). Further analysis revealed that within females, ACL injury increases approximately four-fold from the early stages of adolescence (i.e., 12-13 years old) to the latter stages (i.e., 16-17 years old) (Arendt et al. 1999, Powell and Barber-Foss 2000, Shea et al. 2004), likely via a non-contact mechanism (McNair et al. 1990, Arendt et al. 1999).

As for PFP, Boling and colleagues (2010) reported that females were 2.23 times more likely to develop PFP than their male counterparts (Boling et al. 2010). Further analysis within females revealed a 15-30% incidence rate in girls aged between 13-17 years (Fairbank et al. 1984, Myer et al. 2010). Hence, due to a higher proportion of adolescent female non-contact ACL injury and PFP, these studies highlight the importance of research aimed at investigating injury mechanisms in this population.

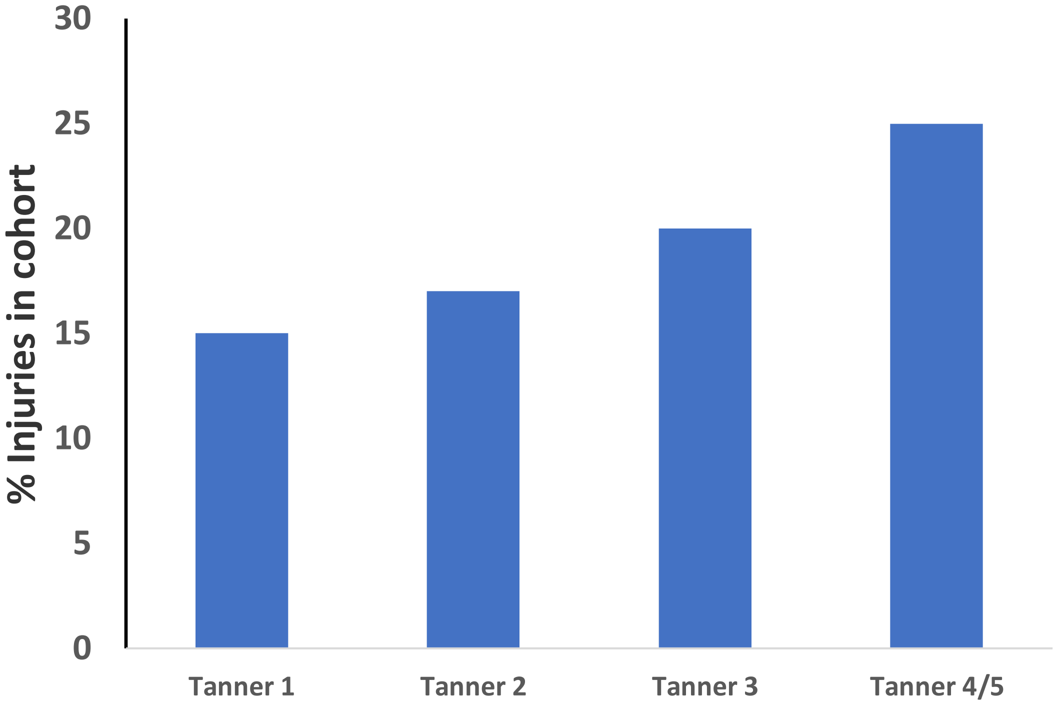


Figure 2.2. Sport related musculoskeletal injuries classified by Tanner stages. Tanner stage 1 represents the pre-pubertal stage and 4/5 the late/post-pubertal stage. A trend of increasing injuries during puberty is evident, whereby a 10% increase is observed from pre- to late/post-pubertal stages. Both male and females across various sports were included in this data. Figure adapted from (Michaud et al. 2001).

2.5. KNEE BIOMECHANICS ASSOCIATED WITH PUBERTAL NON-CONTACT ACL INJURY

Although numerous non-modifiable and modifiable factors have been implicated as contributing factors to non-contact ACL injury amongst females (Posthumus et al. 2009, Quatman et al. 2010, Wild et al. 2012, Sturnick et al. 2015), this thesis is solely focussed upon the role of lower limb biomechanics.

Lower limb biomechanics relevant to ACL injury are widely studied in pubescent cohorts. Typically, external knee joint moments are the primary outcome measures with kinematics (i.e., hip, knee and ankle flexion angles) and ground reaction force (GRF) variables included as secondary outcome measures.

Figure 2.3 depicts external tri-planar knee moments: i) knee abduction moment (KAbM), ii) knee flexion moment (KFM) and, iii) knee internal rotation moment (KIRM). In combination, these three moments increase ACL load and, when excessively high, contribute to ACL rupture (Quatman et al. 2010). Hence, tri-planar knee moments are relevant to knee injury during pubertal development and are discussed separately in the following sections.

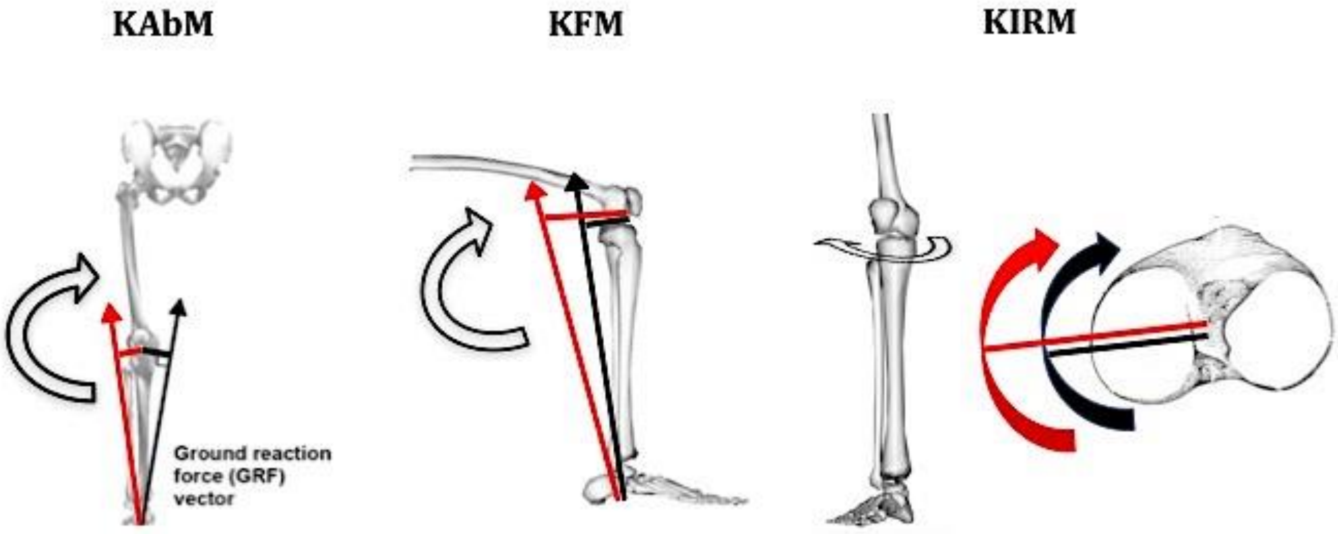


Figure 2.3. External tri-planar knee moments. The product of the GRF vector (black arrow) and perpendicular lever arm (black solid line from knee joint centre) are major contributors to external knee joint moments via inverse dynamics. During landing or running-related tasks, knee moments can increase by manipulation of either parameter, whereby a large GRF vector magnitude and/or lever arm can increase the net moment. In the frontal plane, a laterally directed GRF vector (red arrow; far left image) and lateral lever arm shift can increase KAbM. In the sagittal plane, a greater posterior GRF vector (red arrow; middle image) and associated lever arm can increase KFM. Likewise, a greater transverse plane GRF vector and lever arm can lead to higher KIRM. Together, these moments are referred to as tri-planar knee moments, often associated with non-contact ACL injury and PFP when excessively high.

2.5.1. FRONTAL PLANE KNEE ABDUCTION MOMENT

The frontal plane peak KAbM likely contributes to ACL injury by rotating the knee and leg inwards (i.e., knee valgus), hypothesized as a contributing factor to higher ACL strain and ligament failure (Hewett et al. 2005). Despite the KAbM's association with ACL injury, the findings of studies reporting peak KAbM across the stages of female pubertal development are mixed (see Table 1.2).

Ford and colleagues (2010) examined the landing-related KAbM as pubertal and post-pubertal males and females performed a drop vertical jump (DVJ) from a 31 cm box height (Ford et al. 2010). This study classified participants as pre-, mid- or post-pubertal development via the modified PMOS, in which eight statements regarding PHV, menarche, hair growth, breast development and skin characteristics were ascertained via a yes/no response (Ford et al. 2010). Each participant performed a bilateral DVJ, in which participants dropped off a 31cm high box and immediately rebound vertically with maximal effort. The results revealed an increase in peak KAbM in post-pubertal females (-21.9 ± 13.5 Nm) compared to post-pubertal males (-13.0 ± 12 Nm); however, no gender by pubertal stage differences were observed.

A subsequent study by Sigward and colleagues (2012) also included a DVJ task (box height =36cm) and classified their male and female participants according to pubertal stage via a mix of Tanner stage and PMOS methods (i.e., pre-pubertal, pubertal, post-pubertal and young adult; (Sigward et al. 2012). Like the earlier study by Ford et al. (2010), analysis of variance (ANOVA) revealed no significant gender by puberty interactions for average KAbM. However, when data were collapsed across pubertal stage, females demonstrated a significantly greater average KAbM (0.06 ± 0.03 Nm/kg*m) compared to their matched male counterparts (0.01±0.02 Nm/kg*m, $p<0.005$).

Despite the lack of pubertal stage differences between genders, higher overall peak KAbM in females compared to males has directed research towards pubertal stage comparisons within female cohorts. Recent studies report higher peak KAbM values during puberty, with Wild et al. (2016) prospectively reporting a 250% increase in peak KAbM as girls in Tanner stage 2 grew (Wild et al. 2016), and Kim and Lim (2014) finding a 50% increase from pre- to post-pubertal stages (Kim and Lim 2014). By contrast, Hass et al. (2005) reported no differences in peak KAbM between pre- and post-pubertal girls (Hass et al. 2005), highlighting the between-study variations in peak KAbM findings across female pubertal stages (Table 2.3).

The conflicting findings pertaining to peak KAbM across female pubertal stages are likely due to the wide variation in study methodologies. For instance, Ford et al. (2010) and Sigward et al. (2012) both focused on reporting maturational differences between genders and characterised landing performance using a bilateral DVJ (Ford et al. 2010, Sigward et al. 2012), which in the context of non-contact ACL injury mechanisms, may be irrelevant given that this type of injury primarily occurs during single-limb landing. Support for this notion was provided in a recent study by Krosshaug et al. (2016), which indicated that the DVJ is a poor biomechanical screening tool for ACL injury, as none of the reported biomechanical variables (including peak KAbM) were predictive of the 42 non-contact ACL injuries sustained in their cohort of 710 females (Krosshaug et al. 2016).

These findings have led to the suggestion that single limb landing tasks may be more appropriate in screening pubescent females for ACL injury risk. However, single limb landing studies (Hass et al. 2005, Sigward et al. 2012 A, Kim and Lim 2014, Wild et al. 2016) have reported conflicting findings (see Table 2.3), with additional variations in developmental classification methods and study designs being likely contributors. For example, Wild et al. (2016) performed appropriate characterisation of girls by utilising the Tanner stages (i.e., all girls were at Tanner stage 2; (Wild et al. 2016)), and whilst they prospectively followed this cohort through their adolescent growth spurt, they did not compare their findings to pre- or post-pubertal girls, thereby limiting the relevance of these findings in the context of this thesis. In addition, the studies by Hass et al. (2005) and Kim and Lim (2014) used menarche for pubertal categorisation of pre- and post-pubertal girls (Hass et al. 2005, Kim and Lim 2014). As discussed previously (Section 2.3.1), this is a significant limitation, as menarche is widely variable meaning that girls in the pre-pubertal group could actually have commenced pubertal development and likewise, girls in the post-pubertal group could be at various stages of puberty (i.e., early to post-puberty). Finally, the remaining study by Sigward et al. (2012 A) used reliable pubertal classification methods (i.e., mixed Tanner and PMOS), but surprisingly found no differences between pre-, mid-, post-pubertal and young adult females during single limb cutting task (Sigward et al. 2012 A). Instead, higher peak KAbM in the pre-pubertal group pooled across gender was reported compared to all other groups (Table 2.3). Hence, future studies with more appropriate developmental classification methods, that include a single-limb landing task are required to clarify if peak KAbM does in fact change across female pubertal development and which stage is highest.

2.5.2. KNEE FLEXION AND INTERNAL ROTATION MOMENTS

Although peak KAbM is the primary outcome measure used in most studies investigating non-contact ACL injury, the contribution of sagittal and transverse plane knee moments are also important given that non-contact ACL injury involves a tri-planar mechanism (Quatman et al. 2010, Shin et al. 2011). Surprisingly, only three studies have reported peak KFM during female pubertal development (Hass et al. 2005, Ford et al. 2010 A, Wild et al. 2016).

Hass and colleagues (2005) investigated pre- and post-pubescent females who performed a series of different single-limb landing tasks (i.e., vertical, lateral and static) from a box scaled to each participant's maximal vertical jump height (Hass et al. 2005). Results highlighted maturational differences for all landing tasks, whereby pre-pubescent girls exhibited a higher peak internal knee extension moment (equivalent to external peak KFM) compared to post-pubescent girls. Similarly, Wild et al. (2016) prospectively reported a decrease in peak KFM as girls in Tanner stage 2 (i.e., early puberty) transition through their growth spurt (Wild et al. 2016). In contrast, the study by Ford et al. (2010 A) which characterised the peak KFM during a bilateral DVJ, found that post-pubertal (113.8 ± 29.2 Nm) compared to pubertal (91.1 ± 24.5 Nm) girls landed with a higher sagittal plane peak KFM (Ford et al. 2010 A). Despite the limitation of using a bilateral landing task in the study by Ford et al. (2010 A, as discussed in Section 2.5.1), this highlights the current variation in KFM results between female pubertal groups, clearly indicating more research is needed.

Regarding peak KIRM, the same study previously discussed by Wild et al. (2016), is the only study to date that has reported peak KIRM during a single limb landing task of pubertal girls (Wild et al. 2016). Importantly, results demonstrated an increase in peak KIRM across the four test sessions, whereby girls displayed a lower peak KIRM in test 1 (0.11 ± 0.17 Nm/kg/m) compared to test 4 (0.01 ± 0.13 Nm/kg/m; lower values indicative of higher peak KIRM). Moreover, the study by Kim and Lim (2014) did not report peak KIRM, but they did report a higher peak knee internal rotation angle during single limb landing of post-pubertal (14.67 ± 3.94°) compared to pre-pubertal girls (8.94 ± 3.19°), indicating that peak KIRM may indeed be different between different pubertal groups and worthy of future research (Kim and Lim 2014).

Based on the current evidence pertaining to landing-related tri-planar knee moments during female pubertal development, it is still unclear whether these moments vary across key female pubertal stages. Hence, further research incorporating single-limb landing tasks with appropriate pubertal classification methods are required.

Table 2.3. Summary of studies investigating tri-planar knee moments across puberty. Each study is summarised according to participants, pubertal classification method, biomechanical analysis and specific landing task. The findings are summarised according to those related to female pubertal tri-planar knee moments with a broad summary for each study.

Study	Participants	Classification	Methodology	Task	Knee Moments	Findings	Summary
Ford et al. (2010)	Pubertal (n=182) and post-pubertal (n=133) Boys and Girls.	PMOS	3-D motion analysis (EVaRT) sampling at 240 Hz, two force plates (AMTI) at 1200 Hz.	DVJ off a 31 cm box height	KAbM	Post-pubertal females = -21.9 ± 13.5 Nm Post-pubertal males = -13.0 ± 12 Nm	Higher in post-pubertal females
					KFM	not reported	N/A
					KIRM	not reported	N/A
Ford et al. (2010 A)	Pubertal female (n=145) and males (n=37) and post-pubertal females (n=120) and males (n=13).	PMOS	3-D motion analysis sampling at 240 Hz, two force plates (AMTI) at 1200 Hz.	DVJ from 31 cm box	KAbM	not reported	N/A
					KFM	Pubertal female 91.1 ± 24.5 Nm Post-pubertal female 113.8 ± 29.2 Nm	Higher KFM in post-pubertal compared to pubertal females
					KIRM	not reported	N/A
Sigward et al. (2012)	Pre-pubertal (n=15 females and 16 males), Pubertal (n=15 females and 15 males), Post-pubertal (n=14 females and 14 males) and young adult (n=15 females and 15 males	Tanner	3-D motion analysis (Vicon) with 250 Hz sampling frequency, two AMTI force plates at 1500 Hz	DVJ from 36 cm box	KAbM	Females = 0.06 ± 0.23 Nm/kg•m Males = 0.01 ± 0.15 Nm/kg•m	Higher in females
						Post-pubertal = 0.074 ± 0.11 Nm/kg•m Young-adult = -0.001 ± 0.11 Nm/kg•m	Higher in post-pubertal group (pooled male and females)*
					KFM	not reported	N/A
					KIRM	not reported	N/A

Hass et al. (2005)	Pre-pubescent females (n=16) and post-pubescent (n=16)	Menarche	Genlocked high speed video cameras at 250 fps. One force plate (Bertec) collected GRF at 1000 Hz	Single limb landing (lateral, vertical and static) from DVJ scaled to maximal VJH	KAbM	Pre-pubertal average = -0.0016 ± 0.008 Nm·(kg·BH·√LH)$^{-1}$ Post-pubertal average= -0.0012 ± 0.008 Nm·(kg·BH·√LH)$^{-1}$	No difference averaged across three landings tasks
					KFM	Pre-pubertal Lateral= -0.102 ± 0.004 vertical= -0.0145 ± 0.004 static = -0.0125 ± 0.004 Nm·(kg·BH·√LH)$^{-1}$ Post-pubertal lateral= -0.0073± 0.004, vertical= -0.0076 ± 0.004 static= -0.0088 ± 0.004 Nm·(kg·BH·√LH)$^{-1}$	Higher in pre-pubertals for all landing sequences
					KIRM	not reported	N/A
Kim and Lim (2014)	Pre-pubertal (n = 11) and post-pubertal (n = 11) artistic elite gymnasts	Menarche	3-D motion analysis (Eagle cameras) at 120 Hz sampling frequency. One force plate (AMTI) at 1200 Hz	Single limb drop landing task from 30cm chair	KAbM	Pre-pubertal =0.19 ± 0.09 Nm/kg Post-pubertal = 0.37 ± 0.11 Nm/kg	Higher in post-pubertal girls
					KFM	not reported	N/A
					KIRM	not reported	N/A

Sigward et al. (2012 A)	Pre-pubertal (n=19 females and 19 males), Pubertal (n=21 females and 19 males), Post-pubertal (n=20 females and 18 males) and young adult (n=20 females and 20 males)	Tanner and PMOS	3-D motion analysis (Vicon) with 250 Hz sampling frequency, one (AMTI) force plates at 1500 Hz	Random cued side-step cutting manoeuvre at 45º and 110º via a light signal	KAbM	Pre-pubertal = 1 ± 0.62 Nm/mass·height* Pubertal =0.8 ± 0.62 Nm/mass·height* Post-pubertal =0.6 ± 0.62 Nm/mass·height* Young adult = 0.5 ± 0.62 Nm/mass·height*	Pre-pubertal (pooled male and females) higher than all other groups
					KFM	not reported	N/A
					KIRM	not reported	N/A
Wild et al. (2016)	Pubertal girl (n=33) followed through their PHV	Tanner stage	3-D motion analysis (Optotrak) with 100hz sampling frequency and force plate (Kistler) at 1000Hz	Horizontal leap (single limb) performed at four tests across a year	KAbM	Test 2= -0.13 ± 0.34 Nm/kg/m Test 4= 0.15 ± 0.35 Nm/kg/m	Pubertal girls increase KAbM across their PHV
					KFM	Test 1 =1.32 ± 0.98 Test 4 = 0.73 ± 0.96	No difference across all tests from 1-4
					KIRM	Test 1 =0.11 ± 0.17 Nm/kg/m Test 4 = 0.01 ± 0.13 Nm/kg/m	Pubertal girls increase KIRM across their PHV

GRF = ground reaction force, DVJ = drop vertical jump, PMOS= pubertal maturational observational scale, VJH= vertical jump height, HFM= hip flexion moment, PHV= peak height velocity, KAbM= knee abduction moment, KFM= knee flexion moment, kg= kilograms, KIRM= knee internal rotation moment, Nm=Newton metres, BH= body height, LH= landing height, PHV= peak height velocity. * Denotes approximate values as exact values were not provided in study.

2.5.3. HIP MOMENTS RELEVANT TO ACL INJURY

While tri-planar knee moments are major contributors to ACL injury, proximal hip joint kinetics may also be important given that the proximal kinetic chain has the capacity to influence knee joint mechanics in all three movement planes (frontal, sagittal and transverse (Mendiguchia et al. 2011).

Evidence relating to differences in hip biomechanics across the stages of female pubertal development is limited as most studies only report frontal and sagittal plane moments, possibly because rotational moments are susceptible to larger variation than other planes (Benoit et al. 2006, Schache et al. 2007, Winter 2009). The majority of studies investigating sagittal plane hip biomechanics across female pubertal development have reported a higher peak hip flexion moment (HFM, (Hass et al. 2003, Ford et al. 2010 A), and knee/hip moment ratio (Sigward et al. 2012) at latter compared to earlier stages of pubertal development. In the frontal plane, mixed results have been reported with a higher peak hip adduction moment (HAM) evident by Hass et al. (2003) study in post- compared to pre-pubertal girls, (Hass et al. 2003), while a lower HAM was found by Wild et al. (2016) as girls were prospectively tested across four test session during early puberty (Wild et al. 2016). However, both of these studies have limitations related to pubertal classification which was solely based on age in the study by Hass et al. (2003), and no pubertal group comparisons tested by Wild et al. (2016, (Hass et al. 2003, Wild et al. 2016)). Clearly, these findings may be inconclusive, however as they only report peaks, they do not provide information on bi-planar hip moments (i.e., HAM and HFM) at time of peak knee moments (i.e., KAbM and KFM), which may be more relevant to our understanding of hip joint contributions during landing (Mendiguchia et al. 2011). Consequently, research is needed to determine whether bi-planar hip moments differ between pubertal groups at time of peak KAbM and KFM during landing.

2.6. MECHANISMS UNDERLYING ADOLESCENT PFP DEVELOPMENT

As per the previous section, greater tri-planar knee moments likely contribute to non-contact ACL injury; however, further research is required due to limitations in current methodology and inconsistent findings. Interestingly, evidence suggest that healthy and physically active adolescent females that display higher tri-planar knee moments may also develop other knee pathologies like PFP. In fact, recent evidence related to peak KAbM from Myer and colleagues (2014), demonstrated that the magnitude of knee loads likely predicts whether girls sustain an ACL rupture or develop PFP (Myer et al. 2014). Specifically, larger abrupt braking forces during landing may contribute to an acute ACL rupture, whilst lower threshold, cumulative loading may be more likely to increase retropatella joint stress, a key mechanism thought to contribute to chronic PFP development (Powers 2003, Myer et al. 2014). Therefore, despite the multifactorial aetiology of PFP (Lankhorst et al. 2013), tri-planar knee moments are likely contributors and are discussed in the following sections.

2.6.1. KNEE BIOMECHANICS ASSOCIATED WITH PFP

There is currently no evidence pertaining to running biomechanics between female pubertal stages. Thus, the following section provides an analysis of knee and hip moments between symptomatic and asymptomatic PFP females.

2.6.1.1. SAGITTAL PLANE KNEE LOADING

In contrast to ACL injury, sagittal plane loading is likely the most influential moment influencing PFP development (Novacheck 1998, Novacheck 1998 A, Wirtz et al. 2012, Lankhorst et al. 2013, Bonacci et al. 2014). Higher sagittal plane loads are thought to increase PFJ stress during dynamic tasks such as running. Specifically, an increased peak KFM, combined with an increased peak knee flexion angle (approximately 45° during running), leads to a large amount of force being transmitted through the quadriceps muscles (i.e., rectus femoris, vastus lateralis, vastus medialis oblique) and tendons, subsequently loading the PFJ (Novacheck 1998 A). Given that running is a repetitive task and involves transmission of high loads through the knee joint, this combination of factors can lead to articular cartilage degradation and can also affect the surrounding soft tissue, leading to PFP (Novacheck 1998, Lankhorst et al. 2013).

Whilst this mechanism of PFP development appears plausible, current evidence does not support higher sagittal plane knee loading in females with PFP (Willson and Davis 2008, Besier et al. 2009, Wirtz et al. 2012). For example, Willson and colleagues (2008) collected running-related peak KFM data on adult females with and without PFP (20 participants per group) and revealed similar (~1.3 N*m/kg*m) values for both groups (Willson and Davis 2008). Likewise, Wirtz et al. (2012) found no differences in peak KFM in 20 females with PFP and matched controls (Wirtz et al. 2012), while Besier et al. (2009) who utilised a sophisticated electromyography (EMG)-driven computational musculoskeletal modelling approach also found no differences in peak KFM between females with and without PFP (Besier et al. 2009).

Although these findings do not support a direct link between higher peak KFM and PFP, there are some important limitations to consider. Firstly, these studies were cross-sectional which does not answer whether peak KFM may fluctuate over time and/or whether higher moments are evident before developing the condition. Secondly, participants in all of the aforementioned studies were aged between 21.3-28.8 years, which may not represent an adolescent female population. Moreover, the discussion within many of these studies (Willson and Davis 2008, Besier et al. 2009, Wirtz et al. 2012) acknowledges that participants with PFP may purposely reduce their peak KFM to ameliorate pain associated with higher PFJ loads, a notion supported in a recent systematic review (Lankhorst et al. 2013). Finally, perhaps the most relevant limitation in the context of this thesis is the complete absence of any adolescent and/or pubertal female PFP studies. Hence, running-related pubertal biomechanical studies are required to determine whether differences in peak KFM exist between pubertal developmental stages.

2.6.1.2. FRONTAL PLANE LOADING

Emerging evidence has demonstrated that, in addition to peak KFM, frontal plane loads may also have an important role in the development of PFP. Although no studies have linked higher peak KAbM to abnormal PFJ loading, augmented frontal plane loads are suspected to shift the patella laterally, increasing lateral compartment load and retropatellar forces to a smaller contact area (Powers 2003, Li et al. 2004).

With respect to the literature examining frontal plane loading amongst adolescent females, Myer and colleagues (2010) conducted the only published study investigating peak KAbM in relation to PFP development amongst adolescent females; however, they utlilised a DVJ instead of running (Myer et al. 2010). The research evaluated a cohort of 145 healthy middle and high school adolescent females who were followed over a basketball season, and found that those who developed PFP exhibited a 279% higher KAbM compared to controls (0.024 vs 0.067 Nm/kg) during a DVJ (Myer et al. 2010). More recently, a subsequent study used logistic regression analysis to determine cut-off scores for prediction of PFP, and reported that a frontal plane KAbM >15Nm was associated with a higher risk of developing the condition (Myer et al. 2014).

To provide additional evidence for the role of frontal plane loading in the development of PFP, Holden et al. (2017) prospectively followed 76 females aged 12.9 ± 0.35 years and found that those who developed PFP exhibited 7.79° higher knee valgus angle during a DVJ compared to their uninjured counterparts (Holden et al. 2017). As knee valgus angle is a contributing factor in the calculation of KAbM via inverse dynamics (Winter 2009), these findings provide evidence that peak KAbM may be a relevant variable in the context of adolescent PFP. However, there is currently no data pertaining to running-related peak KAbM across pubertal stages; hence, there is a need for studies examining peak running-related KAbM in pubescent females.

2.6.1.3. TRANSVERSE PLANE LOADING

Unfortunately, there is also no research investigating the relationship between peak KIRM and PFP. However, this is plausible because the contractile force of the quadriceps increases PFJ contact area as the knee flexes through its range of motion during running (Salsich et al. 2003). If quadriceps contractile forces are coupled with femoral internal rotation, the patella can be displaced laterally, directing PFJ forces to the lateral facet, thereby decreasing PFJ contact area and increasing lateral PFJ cartilage stress and, in turn, increasing potential for PFJ injury. Support for this notion is provided by Liao et al. (2015), who investigated PFJ cartilage stress using a finite element model of nine females squatting from 15- 45° (Liao et al. 2015). During the squatting motion, the femur was internally rotated 5° beyond its natural position which significantly increased PFJ cartilage stress via a decrease in PFJ contact area. Therefore, a higher KIRM while running may elevate PFJ stress due to a lower PFJ contact area (i.e., laterally-directed PFJ), increasing risk of developing PFP. As such, given the association between PFP and adolescent females (Powers 2003, Salsich et al. 2003), investigating running-related KIRM at different stages of pubertal development is warranted.

2.6.1.4. HIP MOMENTS RELEVANT TO PFP DEVELOPMENT

The proximal hip joint has the capacity to influence the distal knee joint which may be important with respect to the magnitude of knee joint moments. Not surprisingly, as there are currently no studies investigating running-related tri-planar knee moments during female pubertal development, there is also no data pertaining to hip moments. Nonetheless, previous studies analyzing hip kinematics during running provide evidence to suggest hip moments may be potential contributors to altered knee moments (Willson and Davis 2008, Noehren et al. 2012, Wirtz et al. 2012, Noehren et al. 2013).

A large prospective study conducted by Noehren et al. (2013) concluded that hip biomechanics are important contributors to the development of PFP (Noehren et al. 2013). Specifically, after 400 girls performed an initial running assessment, they were followed for more than two years. During this time, 15 girls (3.8% of total cohort) developed PFP. Analysis of their initial hip kinematics revealed that those who developed PFP displayed approximately 30% higher peak hip adduction angle compared to participants who remained asymptomatic (Noehren et al. 2013). Another study by Noehren et al. (2012) also reported greater hip adduction angles in a PFP cohort compared to healthy controls, with a mean difference of 2.2° (Noehren et al. 2012). Similar hip adduction angles have also been found in other cross-sectional studies of females with and without PFP, supporting the notion that running-related frontal plane hip moments may be relevant to the development of PFP amongst adolescent females (Willson and Davis 2008, Wirtz et al. 2012).

Despite the potential link between frontal plane hip moments and PFP, none of the aforementioned studies have reported hip flexion angles. This is surprising given that sagittal plane hip biomechanics likely contribute to the magnitude of peak KFM and PFJ stress during the stance phase of running by helping distribute load across the knee and hip (Novacheck 1998). However, before the association between hip moments and PFP can be explored prospectively, it is important to understand whether running-related hip moments (i.e., HFM and HAM) at the time of peak knee moments (i.e., KAbM and KFM) differ amongst girls at different stages of pubertal development.

2.7. THE ROLE OF ATHLETIC FOOTWEAR

2.7.1. RATIONALE FOR FOOTWEAR EFFECTS ON KNEE BIOMECHANICS

During recreational sports that are typically associated with ACL rupture and PFP, such as those that involve repetitive running and landing, athletic footwear is typically worn. While there is currently no pubertal research investigating footwear and its effects on knee biomechanics associated with either knee injury in girls throughout puberty, several studies have demonstrated that footwear has the potential to influence knee loads (Joseph et al. 2008, Lindenberg and Carcia 2013, Bonacci et al. 2014, Sinclair 2014, Sinclair et al. 2016). As the foot contacts the ground during dynamic activities (e.g. running or cutting), it dorsiflexes in the sagittal plane, rotates through the midfoot along the longitudinal axis of the foot and everts at the hindfoot about the frontal plane in an attempt to absorb contact forces (Novacheck 1998). Combined, these movements contribute to foot pronation which has been cited as a potential mechanism for the distribution of higher loads to the more proximal segments including the knee (Novacheck 1998, Cheung and Ng 2007).

Given the link between the foot and the knee joint, footwear has been suggested to be a potential intervention to influence foot motion and reduce knee loads. Footwear characterised as high-support typically exhibits increased medial stiffness (i.e., medial post), longitudinal shoe rigidity, heel counter stiffness and midfoot rotational stability (Barton et al. 2009). These footwear characteristics are argued to reduce excessive foot pronation. In support, a systematic review by Radzimski et al. (2012) revealed that high-supportive footwear and medial wedges placed inside shoes to ameliorate excessive foot pronation, influenced the proximal knee joint by increasing the external knee adduction moment (i.e., lower KAbM) amongst healthy people while walking (Radzimski et al. 2012). Arch supports, medial wedges and/or high-supportive shoes may reduce foot pronation by providing a foot inversion bias, shifting the centre of pressure medially, thereby lowering knee moments such as KAbM or KIRM (Franz et al. 2008, Radzimski et al. 2012).

In contrast, laterally stiff footwear and lateral wedges can increase foot pronation leading to a laterally-directed (eversion) bias, shifting the centre of pressure laterally and increasing moments such as KAbM or KIRM (Eslami et al. 2009, Hinman et al. 2012, Bennell et al. 2013, Hatfield et al. 2016). Moreover, footwear pitch defined as the height difference between the heel and forefoot, can actually increase peak KFM and is thought to do so by increasing the ankle dorsiflexion and knee flexion angle, distributing higher loads to the knee during dynamic tasks (Barton et al. 2009, Bonacci et al. 2014, Sinclair 2014). A review of the effects of footwear on tri-planar knee moments during running and landing-related tasks is presented in the following sections.

2.7.1.1. FOOTWEAR EFFECTS ON FRONTAL PLANE KNEE ABDUCTION MOMENT

To date, there is only one study that has investigated the landing-related effects of footwear on peak KAbM (Bisesti et al. 2015). Bisesti et al. (2015) studied fifteen college athletes (seven females and eight males), who performed a 45º lateral cutting manoeuvre in cushioned/low supportive shoes (i.e., no medial post, lower midfoot and longitudinal shoe stiffness) compared to barefoot and results demonstrated no effects of footwear on peak KAbM (Bisesti et al. 2015). These findings may not be surprising given the lack of supportive features that would be typical of high-supportive shoes. Hence, additional research that includes both high- and low-supportive shoes are needed to elucidate whether supportive features influence peak KAbM.

Although there is a lack of research investigating supportive footwear on knee moments, other studies have used surrogate measures of frontal plane knee loading such as knee valgus angle with medial wedge insoles (Joseph et al. 2008, Joseph et al. 2010). In two studies by Joseph and colleagues (Joseph et al. 2008, Joseph et al. 2010), female college athletes were tested with a 5° medial wedge insole compared to an insole with 0° inclination during a DVJ. Although they found a decrease in peak knee valgus angle by 1.21-1.24°, this magnitude of change is relatively small and the lack of peak KAbM data does not clarify whether similar footwear supportive features are efficacious at reducing peak KAbM, particularly in a developmental cohort.

There are also very few studies investigating footwear and/or foot-based interventions on peak KAbM in females during running (MacLean et al. 2006, Lilley et al. 2013). Maclean et al. (2006) investigated the running-related effect of a 5° rearfoot inversion custom-moulded orthotic compared to no orthotic in 15 experienced female runners (mean age of 21.3 years old) and, the results revealed no between-group differences for peak KAbM (MacLean et al. 2006). Similarly, Lilley et al. (2013) compared the effects of low-supportive and high-supportive shoes amongst young (n=15, 18-25 years old) and older females (n=15, 40-60 years old) during running, and also found no differences for peak KAbM. Although these studies may suggest that footwear does not influence the peak KAbM, it is important to note that these studies included relatively small sample sizes (i.e., 15-30 participants), varied foot interventions (i.e., footwear or orthotics) and biomechanical outcome measures (i.e., valgus angle instead of KAbM). Hence, additional studies are required to confirm the landing and running-related effects of different types of footwear on peak KAbM amongst pubescent girls.

2.7.1.2. FOOTWEAR EFFECTS ON SAGITTAL PLANE KNEE FLEXION MOMENT

Previous research supports that footwear has the potential to increase sagittal plane measures such as peak KFM during dynamic tasks, which may be detrimental for both non-contact ACL and development of PFP. To date, no study has investigated the landing or running-related effect of any type of footwear or foot-based intervention on the KFM in young females. This is surprising as many adolescent females will typically wear some form of footwear with or without a foot-based-intervention while playing landing or running sports. Instead, landing literature conducted by Bisesti and colleagues (2015), found that peak KFM increased from barefoot (2.27 ± 0.88 Nm/kg) to low-support shoes (2.54 ± 0.77 Nm/kg) during a lateral cutting task in a cohort of mixed male and female participants (Bisesti et al. 2015). Similarly, Yeow et al. (2011) also found a 30% increase in peak KFM whilst male participants performed a DVJ in low-supportive cushioned court shoes compared to barefoot (Yeow et al. 2011). Despite these findings reported in mixed and male cohorts, it's also possible that similar effects are evident amongst adolescent females, which highlight the need to investigate sagittal plane footwear effects during landing of adolescent girls.

It also appears that higher landing-related peak KFM when wearing footwear is also found in the running literature (MacLean et al. 2006, Kerrigan et al. 2009, Bonacci et al. 2014, Sinclair 2014). For example, Bonacci and colleagues (2014) reported an increase in peak KFM from 3.0 Nm/kg running barefoot to 3.3 Nm/kg wearing low-supportive footwear (Bonacci et al. 2014). Likewise, Sinclair et al. (2014) reported an 18% and 15% increase in peak KFM wearing high-support shoes compared to barefoot and barefoot-inspired shoes (Sinclair 2014). Consequently, it appears that footwear may increase both landing and running-related peak KFM; however, due to the variation in study designs and participant characteristics, it is unknown whether these effects are consistent in a female pubertal cohort or between high- or low-supportive footwear.

2.7.1.3. FOOTWEAR EFFECTS ON TRANVERSE PLANE KNEE INTERNAL ROTATION MOMENT

Currently, there are no studies that have investigated the effects of footwear on peak KIRM in females during landing and running tasks. However, knee internal rotation kinematics have been reported in healthy runners in two studies. Christopher et al. (2006) found no difference in running-related knee internal rotation angle of college aged females wearing a 6° rear foot varus post orthotic compared to no orthotic (Christopher et al. 2006). In contrast, Hutchinson et al. (2015) reported that high-supportive shoes decreased running-related peak knee internal rotation angle (18.6 ±

6.3°) compared to low-supportive shoes (21.9 ± 5.3°) in a cohort of male and female adult runners (Hutchison et al. 2015). Clearly, further research is required to determine whether alterations in peak KIRM is evident across different footwear conditions in a cohort of females throughout puberty.

2.8. SUMMARY

Overall, this literature review has revealed considerable gaps that require investigation. Specifically, the lack of data exploring peak tri-planar knee moments in a female pubertal cohort is concerning given that this population is susceptible to knee injuries. Therefore, determination of whether tri-planar knee moments differ across female pubertal stages will be novel and informative in the context of knee injury mechanisms.

Furthermore, while injury prevention programs are currently endorsed to ameliorate the higher risk of knee injury amongst adolescent females, it is important to develop and incorporate complimentary strategies alongside prevention programs. One alternative may be athletic footwear, which has been largely ignored. This may be an attractive prevention approach given that footwear is relatively low cost, widely available and may be implemented at a population level. For this reason, it is important to establish an understanding of whether commercially available high- and low-support footwear influence tri-planar knee moments of pubescent females during single-limb landing and running.

CHAPTER 3

STUDY 1: *Differences in tri-planar knee moments between stages of female pubertal development*

3.1. CHAPTER OVERVIEW

This chapter examined tri-planar knee moments of girls and young women at three key stages of pubertal development. A single-limb drop lateral jump was utilised to associate findings with biomechanics relevant to female non-contact ACL injury.

This study is currently under peer review at *Medicine and Science in Sports and Exercise* authored by Sayer TA, Hinman RS, Paterson KL, Fortin K, Bennell KL, Timmi A, Pivonka P & Bryant AL. TS, RH, KP, KB, PP and AB conceived the idea for the paper, while TS, KF, AT recruited study participants and collected biomechanical data. TS processed and analysed all biomechanical data and drafted the study manuscript. All authors revised and provided significant input to devise the final manuscript presented in this thesis.

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3.2. INTRODUCTION

Puberty is the transition from childhood to adulthood and typically involves a rapid rise in sex hormones driving substantial growth of the musculoskeletal system (Faust 1977). During early adolescence when physical characteristics of puberty begin to emerge, the incidence of serious knee injuries such as non-contact ACL rupture amongst females is reported to increase approximately four-fold (Shea et al. 2004). The onset of the menstrual cycle (menarche) leads to higher circulating estrogen levels which, in turn, may alter neuromuscular parameters related to ACL injury (Wild et al. 2012). Consequently, female pubertal and hormonal characteristics are suggested to influence aberrant knee biomechanics (Wild et al. 2012), a significant risk factor contributing to higher rates of ACL injury between early compared to late pubertal females (Hass et al. 2005, Kim and Lim 2014, Wild et al. 2016). The external KAbM is commonly evaluated in studies of female pubertal development given its association with ACL injury (Hewett et al. 2005, Sigward et al. 2012, Wild et al. 2016). Furthermore, higher sagittal and transverse plane knee moments (i.e., external KFM and KIRM, respectively) in combination with KAbM are more likely to rupture the ACL via a tri-planar mechanism of injury (Quatman et al. 2010), rather than excessive force in one plane alone.

The majority of previous developmental biomechanics research has evaluated a bilateral DVJ, reporting higher KAbM and KFM in post-pubertal females compared to pubertal counterparts (Hewett et al. 2006, Ford et al. 2010, Sigward et al. 2012). However, the use of a bilateral landing task, in the context of ACL injury mechanisms, lacks external validity because rupture primarily occurs during single limb landing. In fact, recent reports indicate that the DVJ is a poor biomechanical screening tool for

ACL injury (Krosshaug et al. 2016). Thus, single-limb landing may be more appropriate at identifying aberrant biomechanical patterns related to non-contact ACL injury amongst pubescent females.

The few relevant investigations that have reported single-limb landing protocols (Hass et al. 2003, Hass et al. 2005, Kim and Lim 2014) have reported contradictory findings with respect to KFM (Hass et al. 2003, Hass et al. 2005) and KAbM (Hass et al. 2005, Kim and Lim 2014) while no study has reported KIRM between stages of female pubertal development. Differences may be partly due to the use of menarche to classify pubertal development, in which the time of onset can vary considerably and does not reliably categorise pubertal stage (see Section 2.2.1, (Dambhare et al. 2012, Dorn et al. 2013). By contrast, Tanner stages of development provide a more appropriate classification, as they are based on an individual's current stage of biological maturation (Tanner et al. 1976). Hence, investigating whether girls at different Tanner stages exhibit altered tri-planar knee moments during a single limb landing task, will further help identify whether pubertal stage effects knee moments related to non-contact ACL injury.

While higher tri-planar knee moments are major contributors to ACL rupture (Quatman et al. 2010), hip joint kinetics may also be important given that the proximal kinetic chain has the capacity to influence knee joint mechanics (Mendiguchia et al. 2011). Studies investigating hip biomechanics across female pubertal development have, in general, reported higher sagittal plane external HFM (Hass et al. 2003, Ford et al. 2010 A), knee/hip moment ratio (Sigward et al. 2012) and lower HAMs (Hass et al. 2003) in post-pubescent females compared to their pre-pubescent counterparts. However, it is difficult to interpret the influence of hip moments on tri-planar knee moments from these studies given only peak values were reported. Instead, characterisation of bi-planar (HAM and HFM) hip moments at the time of peak knee moments (i.e., KAbM and KFM) are intuitively more relevant to our understanding of hip joint contributions during landing (Mendiguchia et al. 2011).

Altered tri-planar knee and bi-planar hip joint moments during landing are likely contributors to ACL injury during pubertal years (Wild et al. 2012). Given that puberty evokes rapid changes in anthropometrics (Faust 1977), joint moments normalised to body mass and body mass by height are normally suggested to minimise the influence of these factors (Moisio et al. 2003, Norcross et al. 2017). However, differences in body mass and height are also key differences between pubertal stages (Faust 1977); therefore, this Chapter will report both body mass and body mass by height normalised joint moments.

The aim of this study was to compare single-limb landing-related knee (tri-planar) and hip (bi-planar) moments (normalised to body mass and body mass by height) of pre-pubertal, early/mid-pubertal and late/post-pubertal girls. The primary hypothesis was that KAbM would be higher in the late/post pubertal group compared to the early/mid- and pre-pubertal groups, and in the early/mid- compared to pre-pubertal. Similarly, higher KAbM would be accompanied by a higher HAM at time of peak KAbM. The secondary hypotheses was that peak KFM, KIRM and HFM at time of peak KFM would be higher in the late/post-pubertal group compared to early/mid- and pre-pubertal groups, and in the early/mid- compared to pre-pubertal group.

3.3. METHODS

3.3.1. RECRUITMENT

Prior to participant recruitment, ethics approval was obtained from the University of Melbourne Human Ethics Advisory Group (HEAG) and Human Ethics Sub-Committee (HESC), application ID 1442604 (Appendix 1). Following this, all participants in this study were recruited from local sporting clubs, schools and the University of Melbourne campus. Initially, local sporting clubs and schools were contacted for interest in the study from which permission was gained to advertise to their members/students via newsletters, posters and/or brochures. In addition to advertisements, the primary investigator (the PhD candidate) spoke to physiotherapy students and staff within the university’s School of Health Sciences to obtain interest in the project. Finally, towards the middle stages of recruitment, an advertisement was released University wide, that targeted staff with daughters aged between 7- 25 years old. Subsequently, all interested participants and parents/guardians were directed to an online screening process discussed in Section 3.3.3.

3.3.2. INCLUSION AND EXCLUSION CRITERIA

Inclusion criteria were: (i) aged 7-25 years old; (ii) participating in regular physical activity; and, (iii) healthy weight (body mass index (BMI) <30 kg/m^2). Girls were recruited within this age range as this cohort would typically cover girls from pre- to post-pubertal development. Regarding the physical activity requirements, no restriction was set for type or amount of sport played by girls as the thesis findings were to be generalized across a female adolescent population. Finally, BMI was restricted to avoid motion analysis reliability errors with soft tissue artefact in obese individuals (Benoit et al. 2006, Winter 2009).

Exclusion criteria were: (i) history of lower limb injury, knee pain or medical condition affecting walking, running and jumping, (ii) previous ACL, meniscal or PFJ injury, (iii) bi-or tri-phasic oral contraceptive pill (OCP) use, (iv) current use of medically prescribed or over the counter orthotics and (v) unable to speak, write and read English.

3.3.3. SCREENING

Parents of participants who registered interest in this project were initially contacted by telephone or e-mail. The primary investigator (PhD candidate) addressed any questions/concerns that parents/guardians or participants had about the study procedure. Once satisfied, participants >18 years old and/or parents/guardians of daughters <18 years old were sent an online screening form via e-mail. The screening questionnaire ascertained (i.e., yes/no response) whether each of the inclusion/exclusion criteria were satisfied.

If eligible, the primary investigator sent each participant or parent/guardian a plain language statement and consent form, which was signed by participants >18 years old or parents/guardians of participants <18 years old and returned either via e-mail or reply-paid postage.

3.3.4. SAMPLE SIZE

Given the lack of data pertaining to tri-planar knee moments during single-limb landing and female pubertal development, the sample size calculation for this thesis was based upon KAbM data from Kim and colleagues (Kim and Lim 2014). Peak KAbM was assumed to increase substantially from pre- to early/mid-pubertal groups with a smaller increase between the early/mid- and late/post-pubertal girls guided by previous pubertal research during bilateral landing (Hewett et al. 2004, Sigward et al. 2012). Subsequently, moment values of 0.15 Nm/kg, 0.32 Nm/kg and 0.4 Nm/kg were utilised with a within-group standard deviation of 0.15. Power was set at 0.8 and a p value of 0.05 was selected. Accordingly, 31 participants were required for each of the three pubertal groups (i.e., 93 participants in total).

3.3.5. PUBERTAL CLASSIFICATION

Ninety-three recreationally active females (31 per pubertal-group) were recruited based on our sample size calculation and classified into one of three modified phases of puberty: (i) pre-pubertal (Tanner stage 1), (ii) early/mid-pubertal (Tanner stage 2-3 and either growth spurt or menarche) and, (iii) late/post-pubertal (Tanner stage 4-5, both menarche and growth spurt essential) stages. Girls who did not meet the above criteria were excluded from the study.

Tanner staging was based upon self-rated breast development via an online, de-identified questionnaire containing pictures and modified diagrams (see Figure 2.1, Chapter 2; (Tanner et al. 1976, Tanner 1986). The questionnaire also ascertained if the adolescent growth spurt had occurred (yes or no response) using the question "*The* *adolescent has grown 3-3.5 inches (7.5-9cm) in the past 6 months or is past this growth spurt*" and whether menarche had commenced via the statement "*The adolescent has begun menarche (period)*" taken from the modified pubertal maturation observational scale (PMOS; (Davies and Rose 2000, Ford et al. 2010). For girls <12 years of age, all pubertal assessment information was provided by a parent/guardian, whereas girls aged ≥12 years completed the questionnaire themselves to improve reliability and validity (see Section 2.3.3.2; (Chan et al. 2008, Pereira et al. 2014).

3.3.6. ESTRADIOL ANALYSIS AND MENSTRUAL CYCLE CONTROL

Since higher estrogen levels have the capacity to influence lower limb biomechanics (Wild et al. 2012, Balachandar et al. 2017), all girls were tested when estradiol levels were low. For the early/mid- and late/post-pubertal girls who had indicated that their menstrual cycle had commenced, eumenorrheic girls were required to identify their early follicular phase (days 1-7 following menses) at which time biomechanical testing was performed. In contrast, monophasic OCP users were tested at any time, given consistency of estradiol levels. To confirm that all participants were indeed tested with low estradiol levels (including the pre-pubertal group), a 5mL saliva estradiol sample was measured at time of testing, whereby all participants were required to have <18 pmol/L according to the reference ranges provided by the manufacturer (Nutripath Integrative Pathology, Melbourne, Australia). For analysis, saliva samples were stored at -20ºC and subsequently analysed via enzyme immunoassay according to the manufacturer's instructions.

3.3.7. BODY MASS INDEX (BMI) AND HEIGHT

Following saliva collection, body mass was derived from a weighing scale (Model 209, Salter Ltd, Kent, UK) recording in kilograms (kg) to the nearest 500 grams for each participant. At the same time, height was measured via a stadiometer in metres (m) to the nearest millimetre (mm).

3.3.8. MOTION ANALYSIS PREPARTION

Landing 3-Dimensional (3-D) lower limb biomechanics were captured by 12 MX Vicon motion analysis system cameras (Vicon, Oxford, UK) and a 0R6-6-2000 Advanced Mechanical Technology Inc. (AMTI, Inc., Watertown, MA, USA) concealed force plate embedded in the floor. All marker trajectories were captured at 120Hz and GRF data at 2400Hz.

Prior to participant preparation, the laboratory was inspected for any reflective material that could be captured by the cameras followed by a laboratory calibration process. A dynamic calibration involved an MX calibration wand with five reflective markers, manoeuvred in a figure of eight pattern while walking around the force plate. The 12 MX cameras simultaneously recorded the 2-dimensional (2-D) marker positions from which Vicon Nexus software (version 1.8.5) calculated the 3-D position within the laboratory space. The mean calibration residuals were then examined to minimise error of marker measurement. In the event residual error was >1mm, the calibration was performed again (Meldrum et al. 2014). Following this, a static calibration of an L-shaped frame was conducted by placing the frame at the edge of the force plate to calibrate the three planes of reference (sagittal, frontal and transverse), also known as the XYZ global co-ordinate system. All cameras captured three markers on the L-shaped frame which allowed camera orientation to this reference frame.

Marker placement

Each participant changed into a pair of athletic shorts and a t-shirt with holes for designated trunk markers. Non-reflective tape was used to prevent any part of the t-shirt or shorts from obscuring the cameras view of markers. A total of 40 reflective markers (13mm, Figure 3.1) were affixed to the skin using double sided tape according to the configuration described by Schache and Baker (Appendix 2; (Schache and Baker 2007). Each marker was carefully placed according to soft tissue or bony landmarks, palpated by the primary investigator. During the dynamic trails, 34 markers were captured as six markers were removed after static calibration.

Static and dynamic calibration

A static and dynamic knee swinger calibration was conducted to determine the anatomical and technical reference frames of the trunk, pelvis, thigh, shank and foot. (Schache et al. 2006) Specifically, the static trail was performed with participants standing quietly, feet approximately shoulder width apart and arms folded across chest in the centre of the embedded force plate for three seconds. Follow this, a dynamic knee swinger trial was collected in which participants held onto a walking stick or frame to assist balancing on one limb, while the contralateral limb performed five knee “bends” to approximately 45° knee flexion. Knee flexion and extension was used to calibrate the knee joint flexion extension axis and the location of the knee joint centre (KJC) via a dynamic optimisation that located the KJC at the midpoint between the medial and lateral epicondyle markers and rotated the thigh markers about a longitudinal axis line connecting the KJC and hip joint centre (HJC). Subsequently, the mediolateral and anteroposterior axis of the anatomical frame were reoriented and together this allowed characterisation of the knee joint flexion-extension axis (Schache et al. 2006).

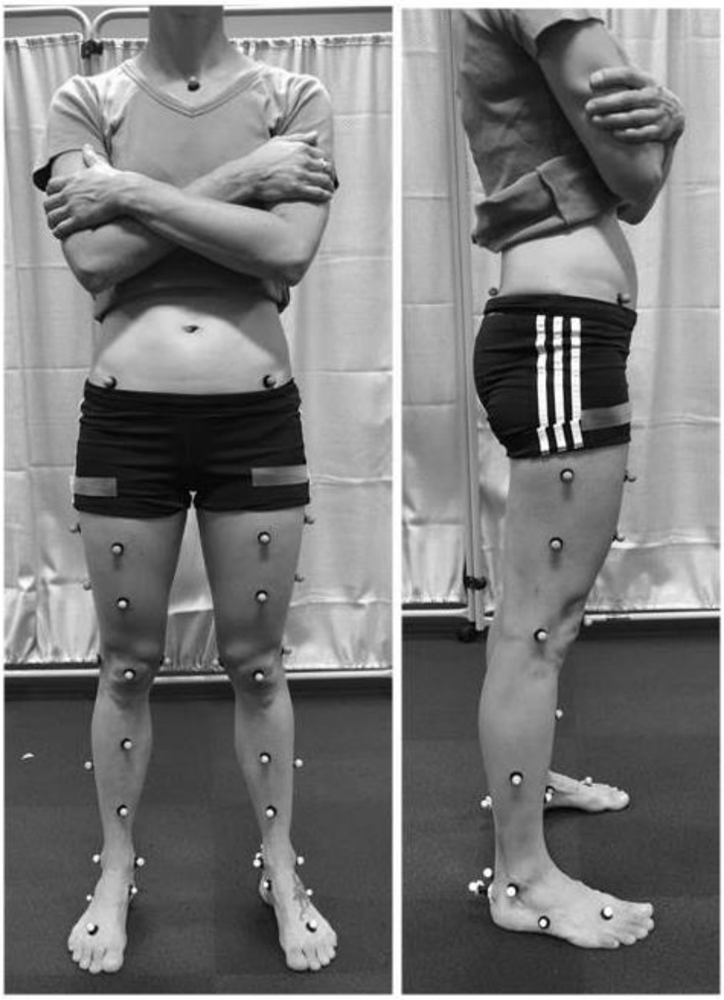

Figure 3.1. Participant prepared for data collection. All 40 (13mm) reflective markers were placed on the trunk, thigh, shank and foot in the biomechanical model previously described. Participants were instructed to fold their hands across their chest (as pictured) for the static calibration.

Processing and cleaning

All trails recorded during the laboratory session were then reconstructed and examined by the primary investigator on Vicon Nexus software (version 1.8.5) using the Nexus reconstruct pipeline. All markers were then labelled according to the model described by Schache et al. (Appendix 2; (Schache et al. 2006). Any missing markers, gaps in marker trajectories, or mislabels captured during the trial were examined by the primary investigator (PhD candidate). In the event a marker was mislabelled, the correct marker was manually selected from the Vicon Nexus marker list. Following this, to fill any marker gaps or correct trajectories, the Nexus copy pattern algorithm was selected using a nearby marker with a similar trajectory.

Once cleaning of data files was complete, the static and dynamic trials were trimmed. For the dynamic trial, the files were trimmed approximately 50-100 frames before heel strike and after toe-off to remove unnecessary data. Finally, both marker trajectories and GRF data were then low-pass filtered using a fourth order zero-lag Butterworth filter at a frequency of 20 Hz, to improve the accuracy of joint moment calculations (Bisseling and Hof 2006).

Kinematic and kinetic analysis

To derive kinematic and kinetic data from the biomechanical model, Vicon Nexus software was again used in conjunction with a custom made Vicon BodyBuilder script (Oxford Metrics, Oxford, U.K.) written by the developer of the kinematic model (Dr. Anthony Schache, Department of Mechanical Engineering, The University of Melbourne). The static calibration was used to estimate the anatomical frame, from which the dynamic knee swinger trial was used to derive the knee join flexion-extension axis as described previously.

The BodyBuilder code was then utilised within the Nexus program to calibrate the kinematic model into eight rigid body segments; trunk, pelvis, thighs, legs and feet (Schache et al. 2006, Schache and Baker 2007). Consequently, during dynamic tasks, the markers were used to locate each segment from which joint angles could be calculated by orientating each segment with respect to the XYZ global co-ordinate system (Schache et al. 2006, Schache and Baker 2007).

Joint moments were calculated from the GRF data, rigid body segments and kinematic data for the hip, knee and ankle. Newton-Euler inverse dynamics was conducted to calculate each external joint moment by incorporating joint position, magnitude and direction of GRF vector (vertical, medial-lateral and anterior-posterior), mass of limb segments and inertial force produced by segmental acceleration of each limb (Winter 2009). Normally, joint moments are then normalised to body mass and height to minimise the influence of anthropometrics, thereby allowing exploration of other factors such as altered movement patterns (i.e. kinematics, GRF and surface EMG; (Moisio et al. 2003, Norcross et al. 2017)). However, in the context of pubertal development, growth-related differences between developmental groups (i.e., body mass and height) may drive differences in knee moments and subsequently lead to joint injury (Faust 1977, Shea et al. 2004). Hence, it is important to understand whether growth-related changes at various stages of puberty contribute to differences in knee and hip moments by normalising to body mass (Nm/kg) and body mass by height (Nm/kg/m) reported in the distal anatomical reference frame. Additional anthropometric segment lengths for the thigh and shank for each participant were also calculated from the kinematic model by estimating the distance in centimetres (cm) from hip joint centre (HJC) to knee joint centre (KJC; thigh length) and KJC to ankle joint centre (AJC; shank length). The filtered kinematic and kinetic data was saved as a co-ordinate 3-D file (C3D) and extracted via a custom written macro into a Microsoft Excel database. Each variable was reported as the mean of three trials.

Biomechanical variables

Peak knee moments (KAbM, KFM and KIRM) and hip moments (HAM and HFM) were derived for this study within the first 25% of stance as ACL injury typically occurs shortly after initial contact (Hewett et al. 2015). Negative values indicate higher KAbM and KIRM and positive values indicate higher KFM, HAM and HFM.

3.3.9. LIMB DOMINANCE

Limb dominance was determined using the footedness subscale of the Lateral Preference Inventory (LPI) (Coren 1993). The footedness subscale of the LPI considers limb preference by asking questions about limb dexterity and co-ordination that are easy for an adolescent population to understand (Coren 1993). Specifically, the primary investigator asked each participant: i) which foot do you kick a ball with? ii) if you wanted to pick up a pebble with your toes, which foot would you use? iii) which foot would you use to step on a bug? and iv) if you had to step up onto a chair, which foot would you place on the chair first? The limb with the highest score was designated the dominant and the opposite limb the non-dominant. None of the participants in this study had an equal number of left or right limb answers for the four questions.

3.3.10. SINGLE LIMB DROP LATERAL JUMP

Previous literature pertaining to landing biomechanics during puberty have utilised a bilateral DVJ task, yet non-contact ACL rupture most likely occurs during single limb stance (Yu and Garrett 2007). Indeed, recent evidence has highlighted the inadequacy of a bilateral DVJ task at identifying biomechanical factors associated with ACL injury (Krosshaug et al. 2016). As a result, the relevance for a single limb landing task that challenges tri-planar knee motion is justified.

Consequently, with previous pubertal single limb landing studies in mind, (Hass et al. 2003, Hass et al. 2005, Wild et al. 2016) a single limb drop lateral (DLJ) jump was developed as outlined in Figure 3.2. The landing task required participants to stand on their non-dominant limb, hands folded across chest (to minimise the influence of the upper limb on landing performance) and toes aligned to the edge of an adjustable steel plyometric box (OEM Engineering Pty Ltd, Melbourne, Australia) 10cm from a concealed force plate (Figure 3.2A). To ensure similar neuromuscular demand between participants, the box height was scaled to 30% of their lower limb length, measured from the outermost lateral aspect of the greater trochanter to the floor of their test limb. Box height was scaled according to individual lower limb anthropometry to create similar neuromuscular demand between participants of different heights given that jump and subsequent landing height increases during adolescence (Temfemo et al. 2009). Hence, landing from a scaled box height is more reflective of the environmental demands imposed on the lower limb of girls of different sizes during sports participation.

The primary investigator then instructed the participant to hop down off the box (Figure 3.2B) and laterally cut quickly towards a piece of tape measured at 150% lower limb length, landing on their contralateral limb and balancing for five seconds (Figure 3.2 C). Following approximately five minutes of familiarity of the single limb DLJ, three successful trials were captured barefoot, in which a successful trial required the participant to perform the task in a controlled manner (i.e., no excessive trunk, pelvic or lower limb movement during landing that could be attributed to poor balance). No instructions were given to participants regarding their jumping technique or quality.

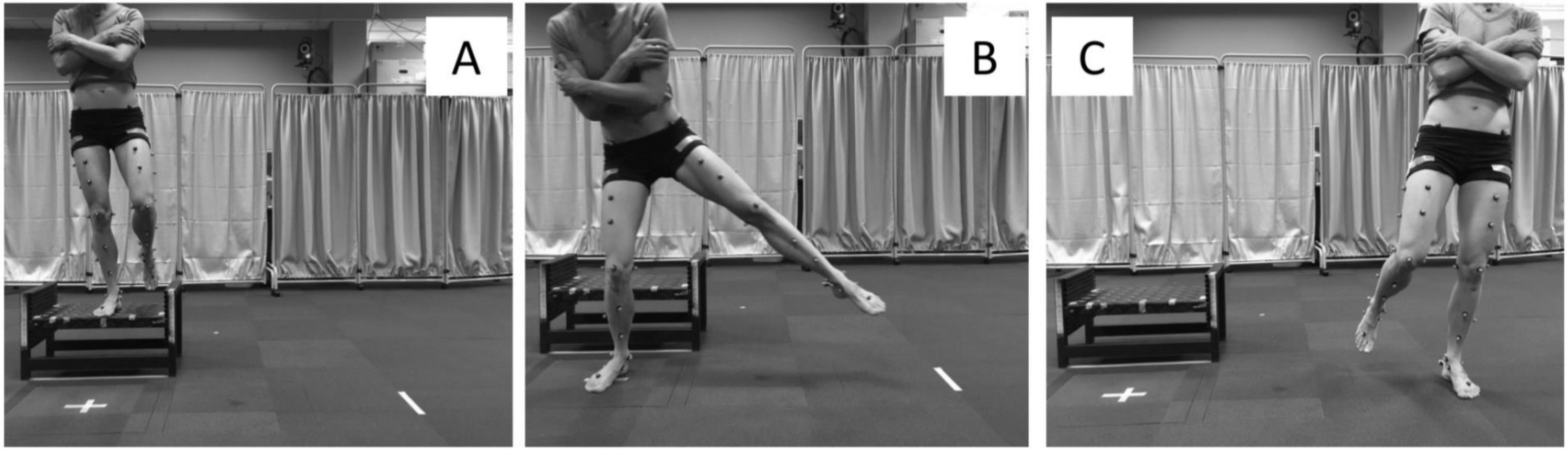

Figure 3.2. Single-limb drop lateral jump task. The participant balanced on their non-dominant test limb with hands folded across chest (A), hopped down towards the “X” marked on the ground (B), and then laterally cut 90º as quickly as possible towards their dominant limb, landing and balancing for 5 seconds (C).

3.3.11. STATISTICS

Means and standard deviations (SD) were calculated for all participant characteristics and biomechanical outcome measures. A one-way analysis of variance (ANOVA) was used to test for differences in participant descriptive characteristics and knee and hip moments between the three pubertal groups. In the event of a main effect, *post-hoc* analyses were performed using Fisher's Least Significant Difference (LSD) tests, with the mean difference (MD), and 95% confidence intervals (CI) reported. Moreover, the effect size was calculated for any main effect and reported as the eta-squared value (η^2), while Cohen's *d* was calculated for any significant pairwise comparisons from the *post-hoc* LSD analysis (Cohen 1988). Cohen's *d* effect sizes were interpreted as: small=0.2, medium/moderate=0.5 and large=0.8 (Cohen 1988). All data were analysed using the Statistical Packages for Social Science (SPSS, version 23, IBM) and significance was set at 0.05.

3.4. RESULTS

Demographic results for the three groups are presented in Table 3.1. As anticipated, there was a difference between groups for age, weight, height and lower limb segment lengths ($p<0.05$). *Post-hoc* analyses demonstrated that the late/post-puberty group was older, heavier and taller with longer thigh and shank segments than both the early/mid- and pre-pubertal groups ($p<0.001$). There were no between-group differences in endogenous estrogen levels ($p>0.05$) between pre-, early/mid- and late/post-pubertal groups. In the late/post-pubertal group, 11/31 girls (34%) had been using a monophasic OCP for >6 months.

Table 3.1. Participant characteristics according to pubertal development. All variables are reported as mean ± SD.

Variable	Pre-pubertal	Early/mid-pubertal	Late/post-pubertal
n	31	31	31
Age (years)	9.4 ± 1.2	11.1 ± 1.4 [a]	19.8 ± 4.0 [a.b]
Weight (kg)	30 ± 5.7	38.4 ± 7.4 [a]	60.5 ± 8.5 [a.b]
Height (m)	1.4 ± 0.1	1.5 ± 0.1 [a]	1.7 ± 0.1 [a.b]
Estradiol (pmol/L)	7.1 ± 5.1	6.7 ± 4.6	9.5 ± 5.1
Thigh Segment Length (cm)	34.9 ± 2.7	38.7 ± 2.7 [a]	43.7 ± 2.1 [a.b]
Shank Segment Length (cm)	31.9 ± 2.5	34.9 ± 2.9 [a]	38.8 ± 2.1 [a.b]

[a] denotes significantly different to pre-pubertal group ($p<0.05$)

[b] denotes significantly different to early/mid-pubertal group ($p<0.05$)

Knee and hip joint moments are shown in Table 3.2. In the frontal plane, a main effect was found for peak KAbM (p= 0.036, η^2=0.07) normalised to body mass, from which subsequent *post-hoc* analyses revealed higher peak KAbM for the late/post-pubertal compared to the pre-pubertal group (MD=-0.09, 95%CI=-0.02 to -0.17 Nm/kg, p=0.015, d=0.61). There were no differences in peak KAbM between the early/mid-pubertal group and either the pre- or post/late-pubertal groups (p>0.05). However, when normalised to body mass by height, no between-group differences were found (p=0.88). At the hip, no between-group differences for HAM at time of peak KAbM were observed (p>0.05, Table 3.2).

In the sagittal plane, there was a main effect of group for peak KFM normalised to body mass (p=0.002, η^2=0.14, Table 3.2). *Post-hoc* analyses revealed higher peak KFM in the late/post-pubertal compared to the pre-pubertal group (MD=0.44, 95%CI=0.19 to 0.68 Nm/kg, p=0.001, d=1.12). In addition, the early/mid-pubertal group demonstrated higher peak KFM compared to the pre-pubertal group (MD=0.28, 95%CI=0.05 to 0.52 Nm/kg, p=0.017, d=0.59). No differences for peak KFM normalised to body mass by height (p=0.30) were found between-groups or the HFM at time of peak KFM for both normalisation methods (p>0.05).

Finally, a main effect of group was found for peak KIRM normalised to body mass (*p*=0.003, η^2=0.12). *Post-hoc* analyses revealed higher peak KIRM in the late/post-pubertal group compared to both the early/mid- (MD= -0.05, 95% CI = -0.09, -0.01 Nm/kg, *p*=0.028, *d*=0.62) and pre-pubertal groups (MD= -0.07, 95% CI= -0.12, -0.03 Nm/kg, *p*=0.001, *d*=0.82). However, there was no difference between the early/mid- and pre-pubertal groups (*p*>0.05). No differences in for peak KIRM normalised to body mass by height were found between groups (*p*=0.19).

Table 3.2. Knee and hip kinetics according to pubertal development. All variables are reported as mean ± SD within the first 25% of stance phase for each developmental group. KAbM and KIRM correspond to negative values, while KFM, HAM and HFM correspond to positive values.

Variable	Pre-pubertal	Early/mid pubertal	Late/post-pubertal
Peak KAbM (Nm/kg)	-0.34 ± 0.11	-0.37 ± 0.13	-0.43 ± 0.18 [a]
Peak KAbM (Nm/kg/m)	-0.25 ± 0.08	-0.25 ± 0.08	-0.26 ± 0.11
Peak KFM (Nm/kg)	2.41 ± 0.41	2.69 ± 0.54 [a]	2.86 ± 0.41[a]
Peak KFM (Nm/kg/m)	1.76 ± 0.31	1.83 ± 0.38	1.72 ± 0.25
Peak KIRM (Nm/kg)	-0.16 ± 0.07	-0.18 ± 0.06	-0.23 ± 0.10 [a,b]
Peak KIRM (Nm/kg/m)	-0.11 ± 0.05	-0.12 ± 0.04	-0.14 ± 0.07
HAM at time of peak KAbM (Nm/kg)	-0.27 ± 0.70	-0.34 ± 0.78	-0.42 ± 0.70

HAM at time of peak KAbM (Nm/kg/m)	-0.21 ± 0.51	-0.25 ± 0.50	-0.24 ± 0.41
HFM at time of peak KFM (Nm/kg)	1.80 ± 0.71	1.57 ± 0.63	1.69 ± 1.14
HFM at time of peak KFM (Nm/kg/m)	1.32 ± 0.51	1.05 ± 0.43	1.04 ± 0.70

[a] denotes significantly different to pre-pubertal group (p<0.05)

[b] denotes significantly different to early/mid-pubertal group (p<0.05)

3.5. DISCUSSION

This is the first study to characterise single-limb landing-related tri-planar knee and bi-planar hip moments in females across stages of pubertal development. These findings demonstrate differences in tri-planar biomechanics of late/post-pubertal girls compared to their early/mid- and pre-pubertal counterparts for body mass normalised, but not body mass by height normalised joint moments.

Findings pertaining to the primary hypothesis of higher peak KAbM in the late/post-pubertal girls compared to pre-pubertal girls are partly supported, given differences between late/post- and pre-pubertal groups for body mass normalised, but not body mass by height normalised KAbM. By contrast, the hypothesis of higher KAbM in late/post- compared to early/mid-pubertal girls, higher early/mid- compared to pre-pubertal girls and higher HAM at the time of peak KAbM is rejected as no between-group differences were found for either body mass or body mass by height normalised data. From the available evidence, the body mass normalised data are consistent with those outlined by Kim and Lim (2014) in a smaller study across two stages of pubertal development (i.e., pre- and post-pubertal), albeit for the dominant limb during a drop and hold task (Kim and Lim 2014). Specifically, post-pubescent elite gymnasts exhibited higher peak KAbM (0.37 ± 0.11 Nm/kg) compared to their pre-pubertal counterparts (0.19 ± 0.09 Nm/kg; (Kim and Lim 2014).

Interestingly, findings related to peak KAbM normalised to body mass by height agree with the findings of studies by Hass and colleagues (Hass et al. 2003, Hass et al. 2005), that also found no differences in peak KAbM (normalised to body mass, height and landing height) between maturational groups in a sample of recreational girls aged between 8-25 years. However, these findings contradict those of Wild et al. (2016) who performed a longitudinal study in which body mass by height normalised peak KAbM was higher in girls at the latter stages of the adolescent growth spurt (i.e., Tanner stage II; -0.13 versus 0.15 Nm/kg/m) during a single limb landing task (Wild et al. 2016). Given the variation in findings for peak KAbM normalised to body mass by height, the present study provides evidence that growth-related changes such as adolescent height (i.e. stature), rather than increased body mass, indeed dictate whether between-group differences are found.

Mechanically, growth-related increases in limb segments during puberty may lead to an increase in the muscular torque required to control the segmental motion of limbs of girls at later compared to earlier stages of puberty (Winter 2009). Indeed, support for the role of adolescent height as a major contributor to higher knee moments was investigated longitudinally by Hewett and colleagues (2015), whereby peak KAbM (i.e. raw data, Nm) increased as a function of increasing tibial length (i.e., adolescent growth spiurt) in females as they performed a DVJ task (Hewett et al. 2015). Clinically, these findings in conjunction with the present study highlight that changes in adolescent height influence tri-planar knee moments which may be important in the context of non-contact ACL injury, given that higher absolute joint load can contribute to joint injury (Hewett et al. 2004, Myer et al. 2014).

With respect to the frontal plane HAM at time of peak KAbM, there were no differences between pubertal groups when the moment was normalised for body mass or body mass by height; in fact, girls demonstrated an external hip abduction moment at time of peak KAbM. This is surprising given that proximal frontal plane hip joint mechanics are recognised as a contributor to distal knee joint mechanics (Mendiguchia et al. 2011); however, no study has characterised the frontal plane HAM with respect to peak KAbM in a pubertal cohort. Hence, these findings may further suggest that growth-related changes (i.e., adolescent height) as previously discussed, rather than frontal plane hip moments, contribute to differences in peak KAbM.

The secondary hypothesis was also partly confirmed, with a higher body mass normalized peak KFM in the late/post-and early/mid- pubertal girls compared to the pre-pubertal girls. However, no differences were found for peak KFM normalised to body mass by height or HFM at time of peak KFM for both normalisation methods. It is plausible that increased adolescent height leads to higher absolute vertical GRF (N), which further contributes to a higher peak KFM during the later stages of puberty (Leppanen et al. 2016). Support for this notion was recently published by Leppanen et al. (2016) who found that from the 15 ACL ruptures sustained in their cohort of 171 adolescent females aged 12-21 years, ACL injured girls had a tendency to land with higher absolute vertical GRF (N) compared to those who remained uninjured (Leppanen et al. 2016). This may be clinically relevant given that a moderate to large effect size (d=0.59-1.12) was found for body mass normalised peak KFM. Since higher peak KFM can displace the tibia anteriorly and potentially increase risk of ACL injury (Quatman et al. 2010, Wild et al. 2012), future studies should consider interventions aimed at lowering peak KFM in girls at the latter stages of puberty.

Finally, the findings of higher body mass but not body mass by height normalised peak KIRM in late/post-pubertal girls compared to early/mid- and pre-pubertal girls are in contrast to those of Wild et al. (2016) who reported an increase in peak KIRM normalised to body mass by height during the female adolescent growth spurt (Wild et al. 2016). Differences between study findings may be attributed to variations in test movements (i.e., single-limb DLJ versus single-limb horizontal hop) that may lead to differences in GRF’s and joint kinematics. Hence, further studies are required to confirm whether growth-related changes during puberty influence peak KIRM across a variety of tasks. Nonetheless, as a moderate to large effect size (*d*=0.62-0.82) for peak KIRM normalised to body mass was found in late/post-pubertal girls compared to pre-pubertal and early/mid- to late/post-pubertal girls, this may have important clinical implications, as a combination of rotational (e.g. KIRM) and valgus (e.g. KAbM) forces can increase ACL strain (Shin et al. 2011) and ACL injury risk.

3.6. CONCLUSION

This study reports higher single-limb landing-related peak KAbM, KFM and KIRM when data were normalised for body mass, but not body mass by height, in late/post-pubertal girls compared to pre-pubertal counterparts. Furthermore, no differences in either HAM at time of peak KAbM or HFM at time of peak KFM were identified. Clinically, this study suggests that increased height at latter stages of puberty, rather than body mass, is a major factor increasing tri-planar knee moments during single limb landing.

CHAPTER 4

STUDY 2: *Effect of footwear on tri-planar knee moments during single limb landing in late/post-pubertal girls*

4.1. CHAPTER OVERVIEW

Based on the findings in Chapter 3, this study examined the effect of footwear (barefoot, high-support and low-support) on tri-planar knee moments of late/post-pubertal girls during a single limb drop lateral jump.

This study is currently under peer review at the *European Journal of Sport Science*, authored by Sayer TA, Hinman RS, Paterson KL, Fortin K, Bennell KL, Timmi A, Pivonka P & Bryant AL. TS, RH, KP, KB, PP and AB conceived the idea for the paper, while TS, KF, AT recruited study participants and collected biomechanical data. TS processed and analysed all biomechanical data and drafted the study manuscript. All authors revised and provided significant input to devise the final manuscript presented in this thesis.

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This study was conducted in collaboration with our industry partner Asics Oceania Pty Ltd. None of the authors received any financial benefit from the results of this study or from the manufacturer external to this study. All research procedures were conducted independently, without Asics Oceania involvement. The results of this study are without fabrication, falsification, or inappropriate data manipulation.

4.2. INTRODUCTION

A high prevalence of ACL injury amongst adolescent girls aged 14-18 years old is multifactorial (Shea et al. 2004); however, hormonal and biomechanical factors are emerging as primary contributors (Wild et al. 2012, Wild et al. 2013, Wild et al. 2016). Adolescence is an important stage in the context of female musculoskeletal development, as it typically involves a rapid influx of estrogen and growth factors, commonly referred to as puberty. Considering puberty involves an increase in height, muscle cross sectional area and overall body mass (Faust 1977), it’s suspected that these physical characteristics may indeed lead to aberrant lower limb biomechanics related to adolescent female non-contact ACL injury. Specifically, higher external tri-planar knee joint moments, such as the KAbM, KFM and KIRM are suspected to contribute to a tri-planar mechanism of ACL rupture (Quatman et al. 2010).

Indeed, the previous study (Chapter 3) highlighted that higher tri-planar knee moments are evident at latter stages of puberty when normalised to body mass but not to body mass by height, highlighting the significant influence that increased height has on knee moments during puberty. Moreover, as girls in the late/post-pubertal group display similar demographic and biomechanical profiles related to ACL rupture (Faust 1977, Myer et al. 2014, Hewett et al. 2015, Wild et al. 2016), this group may be at higher risk of injury. Hence, strategies that ameliorate higher body mass normalised tri-planar knee moments are required.

In reality, barefoot participation is impractical for most sports relevant to non-contact ACL injury and, as such, girls wear various types of athletic footwear during sports participation. Surprisingly, there are no published cohort-specific studies investigating the effects of footwear on knee biomechanics. However, previous research involving both healthy (Joseph et al. 2008, Jenkins et al. 2009 , Lindenberg and Carcia 2013, Bonacci et al. 2014, Sinclair 2014) and populations with knee pathology (e.g. older adults with knee osteoarthritis) (Bennell et al. 2013) have demonstrated a knee load-modifying role of footwear. Specifically, modifying medial and lateral support features of a shoe can influence the resultant frontal (i.e., KAbM) and transverse plane (i.e., KIRM) moments (Joseph et al. 2008, Jenkins et al. 2009 , Bennell et al. 2013, Lindenberg and Carcia 2013, Bonacci et al. 2014, Sinclair 2014) which influence ACL strain (Shin et al. 2011). The athletic footwear market contains a wide variety of both "high-supportive" and "low-supportive" footwear options. High-supportive shoes contain features such as a medial post, increased longitudinal shoe stiffness and midfoot rotational stability which are designed to help minimise excessive foot pronation during activity (Joseph et al. 2008, Joseph et al. 2010), whilst low-supportive shoes do not contain such features and allow more pronation to occur (Barton et al. 2009).

It is thought that the biomechanical effects of excessive foot pronation during single-limb landing are transferred up the kinetic chain in female athletes, contributing to elevated KAbM and KIRM (Loudon et al. 1996, Hewett et al. 2004, Shin et al. 2011). To counteract these loads, a high-supportive shoe with appropriate anti-pronation features (Barton et al. 2009), might potentially reduce KAbM and/or KIRM below barefoot levels (see Chapter 3). In support, footwear studies investigating the effects of wedges/insoles and orthotics on knee biomechanics (Hewett et al. 2004, Joseph et al.

2008, Jenkins et al. 2009 , Lindenberg and Carcia 2013) have demonstrated their influence on knee loads by altering the frontal plane position of the knee relative to the resultant ground reaction force vector (Franz et al. 2008, Hatfield et al. 2016). Specifically, laterally arched/wedged insoles provide a laterally-directed (eversion) bias to the foot shifting the centre of pressure laterally and increasing the KAbM (Hatfield et al. 2016). By contrast, medially arched/wedged insoles create a foot inversion bias, shifting the centre of pressure medially and lowering the KAbM (Franz et al. 2008). Furthermore, a medial arch support also has the capacity to externally rotate the tibia relative to the femur, thereby limiting internal tibial rotation and the magnitude of KIRM during foot-ground contact (Eslami et al. 2009). Hence, it's plausible that high-supportive footwear could attenuate peak KAbM and KIRM during single-limb landing relative to low-supportive footwear, and potentially below those observed during barefoot.

Arguably, footwear also has the potential to increase the risk of non-contact ACL injury by increasing peak KFM during sporting activities. Many athletic shoes possess a raised heel with respect to the forefoot (i.e., pitch; (Barton et al. 2009) – a feature that has been previously shown to increase peak KFM compared to barefoot in adult runners (Bonacci et al. 2014, Sinclair 2014, Sinclair et al. 2015). Given that high-supportive shoes often have an increased pitch compared to their low-supportive counterparts, it's imperative that an examination of high-support footwear includes an analysis of frontal, transverse and sagittal plane knee moments (i.e., KAbM, KIRM and KFM) as many late/post-pubertal girls are likely wearing these types of shoes while playing sport.

Therefore, the aim of this study was to investigate whether a difference in tri-planar knee biomechanics exist between high-support shoes, low-support shoes and barefoot in late/post-pubertal girls. The primary hypothesis was that the high-supportive shoe would exhibit lower peak KAbM and KIRM compared to both the low support shoes and barefoot. In contrast, the secondary hypothesis was that both high- and low-support shoes would increase peak KFM compared to barefoot.

4.3. METHODS

4.3.1. PARTICIPANTS

Participant recruitment, selection criteria, pubertal classification, estradiol analysis and participant height and weight for the late/post-pubertal group are described in detail in Chapter 3, Section 3.3. Briefly, 31 recreationally active females were required to match the relevant classification, Tanner stage of breast development 4-5 with the presence of menarche and the adolescent growth spurt as essential additional characteristics. This study was approved by the University of Melbourne HEAG and HESC (application ID 1442604; Appendix 1). All participants and/or parents/guardians signed an informed consent form.

Considering puberty involves a rapid rise in estrogen (Wild et al. 2012, Balachandar et al. 2017), each participant was tested while estrogen levels were low, as higher levels could influence our external knee joint moment measures (Wild et al. 2012). Essentially, girls that were either eumenorrheic or using a monophasic OCP in the late/post-pubertal group were tested at different times during their menstrual cycle. Only the eumenorrheic girls were required to identify their early follicular phase (i.e., 1-7 days post menses) for biomechanical testing, whereas monophasic OCP users were tested anytime due to consistency of estrogen levels. Confirmation of low estradiol levels was determined in all girls at the time of testing by collecting a 5 mL saliva sample, in which all girls were required to be <18 pmol/L according to the reference ranges for the follicular phase provided by the manufacturer. Samples were analysed via enzyme immunoassay according to the manufacturer's instructions (Nutripath Integrative Pathology, Melbourne, Australia).

Descriptive measures of height and weight were recorded while barefoot (see Section 3.3.7), followed by the LPI (see Section 3.3.9; (Coren 1993)) to identify the non-dominant limb for testing, given that previous literature indicates higher female ACL injury rates on this limb (Krosshaug et al. 2016).

4.3.2. FOOTWEAR CLASSIFICATION

Unfortunately, there is currently no definition or criteria that designates footwear as either high- or low-support. Therefore, shoes were selected based on a set of criteria developed *a priori* from recommendations in the Footwear Assessment Tool (FAT; (Barton et al. 2009). The high-support shoe criteria possessed stability features thought to ameliorate peak KAbM and KIRM, in contrast to the low-support shoe which did not possess these stability features (Appendix 3).

The high-support shoe featured (i) a midsole with a higher density/stiffness medially compared to laterally (e.g. medial post), (ii) <10° torsional stiffness, (iii) <10° heel counter stiffness and (iv) <45° midfoot longitudinal stability (Appendix 3). By contrast, the low-support footwear characteristics included: (i) uniform midsole density (e.g. no medial post), (ii) 10-45° heel counter stiffness (iii) 10-45° torsional stiffness, (iv) >45° midfoot longitudinal stiffness. As a result, the Asics Kayano-GS was selected as the high-support shoe and the Asics Zaraca 3 as the low-support shoe. Further technical features related to the high support shoes (Asics Kayano –GS) include: (i) heel stack height= 25mm, (ii) forefoot stack height= 12mm, (iii) footwear pitch= 13mm and (iv) shoe mass= 260g. For the low support shoes (Asics Zaraca 3) these features included: (i) heel stack height= 28mm, (ii) forefoot stack height= 18mm, (iii) footwear pitch= 10mm and (iv) shoe mass= 240g (Appendix 3). Both shoes were the current model at time of testing.

The presence of a medial post and midsole density was determined by the manufacturer. Longitudinal shoe stiffness was assessed by bending the midfoot of the shoe in the sagittal plane and subjectively rating as moderate rigidity (shoe bends <45°) or mild (shoe bends >45°; (Barton et al. 2009). Similarly, midfoot torsional stiffness was subjectively assessed by rotating the midfoot of the footwear to broadly classify the stiffness as rigid (<10° rotation) or moderate (10-45°). Likewise, heel counter stiffness was determined as per the FAT where the heel counter was clasped with the index finger and thumb approximately 20 mm from its base and squeezed in the frontal plane to estimate its angular displacement (Barton et al. 2009).

4.3.3. FOOT POSTURE INDEX

The foot posture index (FPI) was included as foot pronation may influence knee biomechanics associated with ACL rupture (Loudon et al. 1996, Hewett et al. 2005). Prior to data collection, the primary investigator (PhD candidate) was trained by an experienced sports podiatrist with extensive use of the FPI (co-author KP). Reliability was not conducted, as the FPI intra-rater (ICC=0.93 - 0.94) and inter-rater reliability (ICC=0.79) has previously been shown as good to excellent (Evans et al. 2012).

Initially, participants were instructed to march on the spot, with their feet approximately shoulder width apart to assume a natural static foot alignment. The primary investigator (PhD candidate) then palpated the talar head, the supra and infra lateral malleolar curvature, the height and congruence of the medial longitudinal arch, calcaneal frontal plane position and abduction/adduction of the forefoot compared to rearfoot along the longitudinal axis of the foot. Each criteria was rated between -2 and +2, in which negative values indicate features associated with a supinated posture, while positive values were related to a pronated foot alignment (Redmond et al. 2006).

The summation of each criteria totalled a score between -12 and +12 from which broad classification of foot type could be determined, whereby normal/neutral = 0 to +5, pronated = +6 to +9, severely pronated = 10+, supinated = -1 to -4 and severely supinated = -5 to -12 (Redmond et al. 2006).

4.3.4. SINGLE LIMB DROP LATERAL JUMP

A detailed explanation and illustration of the single limb drop lateral jump is outlined in Chapter 3, Section 3.3.10. Briefly, all participants stood on a box scaled to 30% of their lower limb length for each footwear condition. With their foot aligned to the centre of the box and hands folded across their chest, participants hopped forwards from their test limb and upon landing, immediately cut 90° towards the opposite limb, balancing for 5 seconds on a marker placed on the ground at a distance of 150% lower limb length from the centre of the force plate. Three successful trials were performed in each of the three different footwear conditions: i) barefoot, ii) low-support and, iii) high-support shoes. Testing order of footwear was pre-determined via block randomization for each participant.

4.3.5. MOTION ANALYSIS

An expanded methods section pertaining to laboratory calibration and data analysis is described in Chapter 3, Section 3.3.8. Kinematic (120Hz) and GRF data (2400Hz) were collected using a 12-camera Vicon motion analysis system (Oxford, UK) synchronized with a concealed force plate (AMTI, Inc., Watertown, MA, USA). Data were low-pass filtered using a fourth order zero-lag Butterworth filter at a frequency of 20 Hz. Joint moments were calculated using inverse dynamics and were expressed in the distal anatomical reference frame and normalised to body mass (Nm/kg; (Schache and Baker 2007). Normalisation to body mass and height was not explored in this study as it was a within subject comparison (i.e., girls in the late/post-pubertal group). Negative values indicate higher KAbM and KIRM and positive values indicate higher KFM. Peaks for all moments were derived and exported for analysis. Joint moments were evaluated during the first 25% of stance as ACL injury typically occurs shortly after initial contact (Wild et al. 2016). Anthropometric segment lengths for the thigh and shank were extracted from the kinematic model as described previously (Section 3.3.8), from the HJC to KJC (thigh length) and KJC to AJC (shank length).

4.3.6. STATISTICS

A series of repeated measures ANOVA and analysis of co-variance (ANCOVA) were run for peak KAbM, KFM and KIRM. Statistical comparisons for peak knee moments across footwear conditions with and without FPI as a covariate were performed to determine whether foot posture had any effect. If significant, *post-hoc* analysis was performed using Fisher's LSD tests. All significant variables are reported as the mean and SD, with the MD, 95% CI and effect size. The partial eta-squared value was reported (η_P^2) for significant main effects, while Cohen's *d* was calculated and interpreted as described in Study 1 (Chapter 3) for pairwise comparisons (Cohen 1988). All data were analysed using SPSS (version 23, IBM) and significance was set at 0.05.

4.4. RESULTS

Descriptive characteristics are outline in Table 4.1. For the frontal plane KAbM and transverse plane KIRM, no footwear differences were found with (p>0.05) or without adjusting for FPI (p>0.05, Table 4.2). However, for the peak KFM, there was a main effect for adjusted (p<0.001, η_P^2= 0.74) and unadjusted models (p<0.001, η_P^2= 0.79). In the unadjusted model, *post-hoc* results revealed the high-support shoes had greater peak KFM (MD= 0.44, 95% CI= 0.36, 0.53 Nm/kg, p<0.001, d= 1.11, Table 4.2) than the barefoot condition. Likewise, the low-support shoes contributed to a higher peak KFM (MD= 0.36, 95% CI= 0.25, 0.48 Nm/kg, p<0.001, d= 0.85, Table 4.2) compared to barefoot; however, no differences were observed between shoe conditions. Similar results were obtained for pairwise comparisons in the adjusted model for FPI (Table 4.2).

Table 4.1. Descriptive characteristics of the late/post-pubertal group. All variables are reported as mean ± SD. FPI values between 0-5 indicate neutral alignment, >5 pronation and <0 supination.

Variable	Late/post-puberty
n	31
Age (years)	19.8 ± 4.0
Weight (kg)	60.5 ± 8.5
Height (m)	1.7 ± 0.1
Estradiol (pmol/L)	9.5 ± 5.1
Thigh Segment Length (cm)	43.7 ± 2.1
Shank Segment Length (cm)	38.8 ± 2.1
FPI	2.5 ± 3.6

Table 4.2. Peak tri-planar knee moments for each footwear condition. Results are presented as mean ± SD. Negative values represent a larger peak KAbM and KIRM, whereas for the KFM, positive values indicate a larger peak moment. Data are presented for adjusted and unadjusted covariate analysis of FPI.

	Adjusted			Unadjusted		
Variables	Barefoot	High-support	Low-support	Barefoot	High-support	Low-support
KAbM (Nm/kg)	-0.43 ± 0.18	-0.41 ± 0.21	-0.47 ± 0.16	-0.43 ± 0.18	-0.41 ± 0.20	-0.44 ± 0.16
KFM (Nm/kg)	2.85 ± 0.43	3.3 ± 0.39 [a]	3.22 ± 0.41[a]	2.90 ± 0.42	3.3 ± 0.39 [a]	3.22 ± 0.41[a]
KIRM (Nm/kg)	-0.23 ± 0.11	-0.25 ± 0.11	-0.23 ± 0.09	-0.23 ± 0.11	-0.25 ± 0.11	-0.23 ± 0.09

[a] denotes significantly different to barefoot group ($p<0.05$)

4.5. DISCUSSION

This is the first study to compare the effects of different footwear conditions on tri-planar knee moments in a cohort of girls classified as late/post-pubertal development during a single-limb landing task. These findings reject the primary hypothesis, as the high-support shoe did not ameliorate peak KAbM and KIRM compared to low-support and barefoot conditions. However, as expected, the secondary hypothesis was confirmed as both shoe types increased peak KFM compared to barefoot. Given these findings, it appears that both high- and low-supportive styles of footwear are inadequate at reducing peak KAbM and KIRM and in fact increase peak KFM, which may be detrimental for reducing the risk of non-contact ACL injury in this cohort (Quatman et al. 2010).

Regarding the primary hypothesis related to both peak KAbM and KIRM, these findings extend those reported by Bisesti and colleagues (Bisesti et al. 2015) who reported no difference in KAbM between barefoot and low support shoes in a mixed cohort of adult participants who performed a 45° cutting task. However, findings in this study contrast those previously reported investigating orthotics (Jenkins et al. 2009) and medial post/wedges (Joseph et al. 2008, Joseph et al. 2010), which demonstrates the significant effect foot-based interventions can have on frontal plane biomechanics during landing-related tasks. Specifically, two studies by Joseph and colleagues (Joseph et al. 2008, Joseph et al. 2010) highlight that knee valgus, foot pronation and hip adduction angles are all reduced when female college athletes wore a 5° medial wedge compared to no post. In light of these results, it appears that the supportive features in the high-support shoes are inadequate to substantially influence frontal and transverse plane knee moments, and perhaps the addition of a foot orthotic may provide a more favourable effect. Furthermore, adjusting for FPI did not affect either frontal or transverse plane loading results. As the average FPI in our cohort was 2.5 ± 3.6 which is categorized as a normal foot posture, it may be that the high- and low-support shoes effect on moments were diminished and may be more pronounced in pronated foot types. Indeed, support for this theory comes from a recent randomized controlled trial investigating the effect of standard and motion control footwear in runners, that demonstrated lower injury risk in runners who wore the motion control shoe and had a higher FPI score (i.e., pronated foot; (Malisoux et al. 2016). Therefore, further FPI sub-group analysis is recommended in future studies.

The secondary hypothesis was confirmed with higher peak KFM (≈10-12%) evident when landing in shoes compared to barefoot. This is probably due to a combination of elevated pitch and stack height (i.e. the amount of cushioning between the foot and ground, Appendix 3) in each shoe, which reduces sagittal plane ankle excursion and increases knee flexion angle during landing, leading to a larger sagittal plane knee joint moment arm, subsequently causing higher KFM (Bonacci et al. 2014). In support, previous drop-landing studies have demonstrated a 22% increase in knee flexion angle at initial contact and a 4% increase in peak knee flexion angle with increasing heel heights (i.e., pitch; (Lindenberg and Carcia 2013). Similarly, other research investigating running has reported approximately 18% lower KFM when running barefoot (i.e., lower pitch) compared to supportive athletic footwear (i.e., higher pitch) (Sinclair 2014). Considering both high and low-supportive shoes possessed a higher pitch (13mm and 10mm respectively) compared to barefoot, it is likely that this alone causes increased KFM. More importantly, these findings are an important clinical finding for footwear prescription, as the effect size was large (*d*> 0.80) suggesting that footwear dramatically increases peak KFM during single-limb landing. Since many girls will wear similar types of shoes while playing sports in which ACL rupture occurs, these shoes may increase the risk of knee injury in late/post-pubertal girls.

While this study provides new insights into the effect of athletic footwear, several limitations should be acknowledged. Firstly, the cross-sectional study design does not reveal whether different types of footwear influence knee moments over time. Although speculative, an adaptation period may be required for participants to become accustomed to different types of footwear, which may ultimately lead to neuromuscular changes that result in lower peak knee moments, rather than instantaneous change measured in this study. Secondly, the selected footwear was based on criteria developed from previous literature (Barton et al. 2009), yet there is the potential limitation of extrapolating results to other footwear styles, or similar styles from other footwear manufacturers. Finally, both adjusted and unadjusted FPI values were reported to determine if FPI affected knee moments, yet it is not known whether FPI sub-types, particularly those with a pronated foot, are influenced to a further extent than supinated counterparts while wearing different shoes.

4.6. CONCLUSION

High-support and low-supportive shoes do not ameliorate peak KAbM or KIRM compared to barefoot during single limb landing. In fact, both shoes exhibit higher peak KFM compared to barefoot which may be detrimental in the context of non-contact ACL prevention. Specifically, further research is recommended to determine which footwear features are more likely to reduce knee moments during landing of pubertal girls.

CHAPTER 5

STUDY 3: *Differences in hip and knee running moments across female pubertal development*

5.1. CHAPTER OVERVIEW

This chapter examined differences in running-related tri-planar knee moments across female pubertal development. Results from this study help inform whether puberty may affect biomechanics associated with patellofemoral injuries such as PFP.

This study has been accepted at *Medicine and Science in Sports and Exercise* on 08/12/17 authored by Sayer TA, Hinman RS, Paterson KL, Fortin K, Bennell KL, Timmi A, Pivonka P & Bryant AL. TS, RH, KP, KB, PP and AB conceived the idea for the paper, while TS, KF, AT recruited study participants and collected biomechanical data. TS processed and analysed all biomechanical data and drafted the study manuscript. All authors revised and provided significant input to devise the final manuscript presented in this thesis.

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5.2. INTRODUCTION

Puberty is synonymous with adolescence and involves substantial growth of the musculoskeletal system, in which a rapid rise in sex hormones signal long bone growth, cartilage adaptations and muscle development (Faust 1977, Moshang 2005). Importantly, these pubertal growth-related changes do not occur simultaneously and lower limb bone growth precedes cartilage and neuromuscular adaptations (Tanner 1962, Faust 1977). Furthermore, as estrogen gradually rises during female pubertal development, increased ligamentous laxity becomes apparent (Wild et al. 2012). In combination, these musculoskeletal and hormonal changes during puberty may influence lower limb biomechanics associated with musculoskeletal injury (Michaud et al. 2001, Wild et al. 2012, Balachandar et al. 2017).

In this respect, altered tri-planar knee biomechanics including a higher peak KAbM, KFM and KIRM, may contribute to the higher incidence of knee injuries in pubescent females compared to their male counterparts (Myer et al. 2010, Sigward et al. 2012, Stracciolini et al. 2013, Wild et al. 2016). Indeed, Study 1 (Chapter 3) demonstrated that changes in height, rather than body mass at the latter stages of puberty may explain increased tri-planar knee moments when landing (compared to pre-pubertal counterparts), which may subsequently increase risk of knee injuries such as non-contact ACL rupture (Quatman et al. 2010). Similar findings may also be observed in other recreational tasks such as running and thereby have implications for the development of other knee pathologies such as PFP (Fairbank et al. 1984, Novacheck 1998 A, Myer et al. 2010).

Although the aetiology of PFP is multifactorial (Fulkerson and Arendt 2000, Lankhorst et al. 2013, Crossley et al. 2016), increased peak KFM has been linked with

PFJ stress (Bonacci et al. 2014) and has been shown to contribute to patellofemoral cartilage degradation (Teng et al. 2015), which can exacerbate symptoms. Furthermore, elevated peak KAbM in adolescent girls during a DVJ predicts future development of PFP (Myer et al. 2014). While there is currently no evidence pertaining to the role of KIRM, femoral internal rotation increases PFJ cartilage stress in symptomatic PFP individuals, suggesting it may also contribute to PFP risk (Liao et al. 2015). Higher knee moments may also be a result of altered proximal hip joint biomechanics (Mirzaie et al. 2016, Neal et al. 2016). Although no kinetic data exists pertaining to PFP, a higher peak hip adduction and lower peak hip flexion angle have been found to contribute to PFP risk (Neal et al. 2016), supporting the notion that hip moments such as the external HAM and HFM may be important parameters contributing to higher knee moments associated with adolescent PFP.

There is currently no running-related evidence of the aforementioned knee or hip parameters during puberty of adolescent girls. However, studies investigating the landing biomechanics of healthy girls have shown that post-pubertal females exhibit greater peak KAbM compared to their pre-pubertal counterparts (Hewett et al. 2004, Kim and Lim 2014, Wild et al. 2016). In contrast, the findings for peak KFM are mixed (Hass et al. 2003, Hass et al. 2005) and there are currently no studies reporting peak KIRM across puberty, albeit a higher knee internal rotation angle has been shown in post-pubertal compared to pre-pubertal girls (Kim and Lim 2014). Moreover, investigating hip moments relative to knee moments (i.e., HAM at time of peak KAbM and HFM and time of peak KFM) during running is relevant as no previous studies have reported these variables and hip moments may affect knee moments as part of the kinetic chain during running (Novacheck 1998). Previous landing-related literature demonstrates a higher sagittal plane knee/hip moment ratio (i.e., higher external KFM and decreased HFM; (Sigward et al. 2012) in post-pubertal compared to pre-pubertal girls during a DVJ landing task. In the frontal plane, Hass and colleagues (2003) reported that post-pubertal girls had a lower peak HAM than their pre-pubertal counterparts during a lateral cutting task (Hass et al. 2003). That being said, lateral cutting is a vastly different compared to running (Novacheck 1998). Hence, given the limited running literature pertaining to both knee and hip moments during puberty and, in light of results presented in Study 1 (Chapter 3), it is important that further studies determine whether running-related tri-planar knee (i.e., KAbM, KFM and KIRM) and hip (i.e., HFM at time of peak KFM and HAM at time of peak KAbM) moments normalised to body mass and body mass by height differ between pubertal stages.

Therefore, the primary aim of this study was to determine if peak tri-planar knee moments during running differ between three stages of female pubertal development (i.e., pre-pubertal, early/mid-pubertal and late/post-pubertal). The secondary aim was to determine if frontal and sagittal plane hip moments at the time of peak knee moments differ between pubertal stages. The primary hypothesis was that peak KAbM, KFM and KIRM would be greater in the late/post-pubertal girls compared to the early/mid- and pre-pubertal girls when normalised to body mass, but not body mass by height based on findings presented in Study 1 (Chapter 3). Similarly, the secondary hypothesis was that the early/mid-pubertal girls would also exhibit higher peak KAbM, KFM and KIRM than pre-pubertal girls for body mass but not body mass by height normalised moments. Finally, the third hypothesis was that a greater HAM at time of peak KAbM, and a lower HFM at time of peak KFM, would be found in the late/post-pubertal girls compared to the early/mid- and pre-pubertal groups for body mass but not body mass by height normalised moments.

5.3. METHODS

5.3.1. PARTICIPANTS

Participants and methodology were similar to Chapter 3. Briefly, ninety-one recreationally active females were recruited based on inclusion criteria: (i) aged 7-25 years old; (ii) participating in weekly physical activity; and (iii) healthy weight (i.e., BMI <30 kg/m^2). Participants were excluded if they: (i) had a history of lower limb injury, knee pain or medical condition that currently affected walking, running or jumping, (ii) previous ACL, meniscal or PFJ injury, (iii) bi-or tri-phasic OCP use, (iv) current use of medically prescribed or over the counter orthotics and (v) unable to speak, write and read English. Written informed consent was obtained from girls >18 or parents/guardians <18 years old upon eligibility. The protocol was approved by the University of Melbourne HEAG and HESC (application ID 1442604; Appendix 1).

Pubertal classification was performed in the same manner as Chapter 3, Section 3.3.5. To summarize, participants were categorized according to a modified Tanner staging (Tanner et al. 1976, Tanner 1986) that included additional characteristics of puberty: pre-pubertal (Tanner stage 1), early/mid-pubertal (Tanner stage 2-3, either growth spurt or menarche present) and late/post-pubertal (Tanner stage 4-5, both growth spurt and menarche essential). For the early/mid-pubertal classification, participants were required to answer ‘yes’ to either question and indicate they were Tanner stage 2-3. In the event a girl indicated Tanner stage 2-3 and both additional characteristics or Tanner stage 4-5 and no additional characteristics, they were excluded from the study. The pre-pubertal classification required participants to answer ‘no’ for both questions and indicate they were Tanner stage 1.

Given that rising estrogen levels during puberty may influence PFJ mechanics (Faust 1977, Fulkerson and Arendt 2000, Bryant et al. 2011), estradiol was again controlled in the same manner as Study 1, Chapter 3 (see Section 3.3.6). Once again, to confirm that all girls were tested while estradiol levels were low, a saliva sample (5mL) was provided and subsequently stored at -20ºC, followed by enzyme immunoassay analysis (Nutripath Integrative Pathology, Melbourne, Australia). Concentration was reported in pmol/L and all participants were required to have <18 pmol/L according to the reference ranges for the follicular phase provided by the manufacturer.

Following saliva collection, the dominant limb was selected for testing via the footedness subscale of the LPI (Coren 1993), outlined in Chapter 3, Section 3.3.9. Finally, each participant’s height and weight was recorded while barefoot.

5.3.2. RUNNING TASK

The specifics of the running task were then described to participants using a standardized set of instructions that emphasized the importance of completing each trial using their natural running style while barefoot. Before data collection, participants were allowed approximately five minutes to familiarize themselves with running barefoot in the laboratory. A trial was considered successful if i) the foot of the test limb made complete contact with the concealed force plate (i.e., foot was inside the borders of the force plate) and ii) participants ran at 2.8-3.2 m/s as measured via photoelectric timing gates on either side of the force plate. Running speed was controlled because variations between participants can affect joint kinematics and GRF that can subsequently influence net joint moments (Winter 2009). To ensure that all participants ran at the same speed, velocity was measured (m/s) from the mid-point between the anterior superior iliac spine markers (ASIS, see Appendix 2) from the biomechanical model. The average velocity was derived for each of the three trials from which the overall average velocity was calculated. In the event the participant either ran too quickly or slowly, they were advised to modify their speed accordingly until the required speed was attained. Three successful trials were recorded for each participant.

5.3.3. MOTION ANALYSIS

A detailed explanation of the motion analysis procedure is discussed in Chapter 3, Section 3.3.8. 3-D joint moments were derived from marker trajectories (120Hz) and GRF data (2400Hz) captured from a 12-camera Vicon motion analysis system (Oxford, UK) synchronized to a concealed force plate (AMTI, Inc., Watertown, MA, USA). External joint moments for peak KAbM, KFM, KIRM, HAM at time of peak KAbM and HFM at time of peak KFM were calculated using inverse dynamics expressed in the distal anatomical reference frame and normalised to i) body mass (Nm/kg) and ii) body mass by height (Nm/kg/m; (Schache and Baker 2007)). Negative values indicate higher KAbM and KIRM and positive values indicate higher KFM, HAM at time of KAbM and HFM at time of KFM. Peaks for all moments were derived across the whole stance phase. Once again anthropometric segment lengths for the thigh and shank across each pubertal group were also calculated from the kinematic model from HJC to KJC (thigh length) and KJC to AJC (shank length; see Section 3.3.8).

5.3.4. STATISTICS

Means and SD were calculated for all participant characteristics and biomechanical outcome measures. A one-way ANOVA was used to test for differences in participant characteristics, running velocity and joint moments between the three pubertal groups. In the event of a significant main effect, *post-hoc* analyses were performed using Fisher's LSD tests with the MD and 95% CI reported. In addition, the effect size was calculated for any main effect and reported as the eta-squared value (η^2), while Cohen's *d* was calculated and interpreted as described in Study 1 (Chapter 3) for pairwise comparisons (Cohen 1988). All data were analysed using SPSS (version 23, IBM) and significance was set at 0.05.

5.4. RESULTS

Participant characteristics are presented in Table 5.1. As expected, there were differences for age, weight, height, thigh and shank segments lengths between pubertal groups (Table 5.1, $p<0.05$). Specifically, girls in the late/post-pubertal groups were significantly older ($p<0.001$), heavier ($p<0.001$), taller ($p<0.001$) and had longer segments ($p<0.001$) than their early/mid- and pre-pubertal counterparts. Similar differences were found between early/mid- and pre-pubertal girls ($p<0.001$). There was no difference in estradiol concentration between groups on the day of testing (Table 5.1, $p>0.05$).

Running kinetics for the three pubertal groups are presented in Table 5.2. There was no difference in running velocity between the three pubertal groups ($p=0.73$, Table 5.2). Regarding peak KAbM and KIRM, no significant main effects were identified for body mass or body mass by height normalised moments (*p*>0.05). However, a main effect for peak KFM normalised to body mass was found (*p*=0.002, η^2= 0.12), whereby the late/post-pubertal group had a higher peak KFM compared to the pre-pubertal group (MD= 0.40, 95% CI= 0.18, 0.63 Nm/kg, *p*=0.001, *d*= 1.01). Similarly, the peak KFM in the early/mid-pubertal group was also higher than in the pre-pubertal group (MD= 0.24, 95% CI= 0.02, 0.47 Nm/kg, *p*=0.034, *d*= 0.52). There were no differences between the late/post- and early/mid-pubertal groups (*p*=0.16). No differences were found when peak KFM was normalised to body mass by height (*p*= 0.13).

At the hip, a main effect was found for the HAM at time of peak KAbM for body mass normalised data (*p*=0.01, η^2= 0.31), with all groups showing a hip *abduction* rather than adduction moment (i.e., all values were negative; Table 5.2). Specifically, girls in the late/post-pubertal (MD= -0.31, 95% CI= -0.51, -0.11 Nm/kg, *p*=0.003, *d*= 0.86) and early/mid-pubertal groups (MD= -0.21, 95% CI= -0.42, -0.01 Nm/kg, *p*=0.039, *d*= 0.53) ran with a lower HAM at time of peak KAbM compared to girls in the pre-pubertal group. There was no difference between the late/post and early/mid-pubertal groups (*p*=0.358). A main effect was also found for the HAM at time of peak KAbM for body mass by height normalised data (*p*=0.03, η^2=0.07). *Post-hoc* analysis revealed similar effects to body mass normalised data, with lower HAM at time of peak KAbM in the late/post- (MD= -0.17, 95% CI= -0.03, 0.31 Nm/kg/m, *p*= 0.016, *d*= 0.69) and early/mid-pubertal groups (MD= 0.14, 95% CI= -0.001, -0.28 Nm/kg/m, *d*= 0.60) compared to pre-pubertal girls.

Similarly, a main effect for the HFM at time of peak KFM for body mass normalised (*p*<0.001, η^2= 0.31) and body mass by height normalised data (*p*<0.001, η^2= 0.34) was found. *Post hoc* tests revealed a lower HFM at time of peak KFM for body mass normalised data in the late/post-pubertal group compared to both the early/mid- (MD= 0.47, 95% CI= 0.65, 0.28 Nm/kg, *p*<0.001, *d*=1.27) and pre-pubertal groups (MD= 0.54, 95% CI= 0.36, 0.73 Nm/kg, *p*<0.001, *d*=1.42). There were no significant differences between the early/mid- and pre-pubertal girls (*p*>0.05). For HFM at time of peak KFM for body mass by height normalised data, the late/post-pubertal group also had a lower moment compared to the early/mid- (MD= 0.32, 95% CI= 0.44, 0.20 Nm/kg/m, *p*<0.001, *d*= 1.38) and pre-pubertal groups (MD= 0.40, 95% CI= 0.53, 0.28 Nm/kg/m, *p*<0.001, *d*= 1.59). No differences were found between the early/mid- and pre-pubertal girls for either body mass and/or body mass by height normalised data (*p*>0.05).

Table 5.1. Participant characteristics according to pubertal development. All variables are reported as mean ± SD.

Variable	Pre-pubertal	Early/mid-pubertal	Late/post-pubertal
n	31	30	30
Age (years)	9.4 ± 1.1	11.2 ± 1.4 [a]	20.0 ± 4.0 [a.b]
Weight (kg)	30.0 ± 5.7	38.6 ± 7.5 [a]	60.8 ± 8.8 [a.b]
Height (m)	1.4 ± 0.1	1.5 ± 0.1 [a]	1.6 ± 0.1 [a.b]
Estradiol (pmol/L)	7.1 ± 5.1	6.7 ± 4.7	9.6 ± 5.2
Thigh Segment Length (cm)	34.9 ± 2.7	38.7 ± 2.6 [a]	43.7 ± 2.2 [a.b]
Shank Segment Length (cm)	31.9 ± 2.5	34.7 ± 2.8 [a]	38.8 ± 2.2 [a.b]

[a] denotes significantly different to pre-pubertal group ($p<0.05$)

[b] denotes significantly different to early/mid-pubertal group ($p<0.05$)

Table 5.2. Hip and knee joint moments between pubertal stages. All variables are reported as mean ± standard deviation for each developmental group. Higher KAbM and KIRM is indicated by negative values, while higher KFM, HAM and HFM is indicated by positive values.

Variable	Pre-pubertal	Early/mid-pubertal	Late/post-pubertal
Running velocity (m/s)	3.06 ± 0.24	3.06 ± 0.26	3.10 ± 0.18
Peak KAbM (Nm/kg)	-0.25 ± 0.07	-0.29 ± 0.10	-0.28 ± 0.09
Peak KAbM (Nm/kg/m)	-0.18 ± 0.05	-0.20 ± 0.07	-0.17 ± 0.06
Peak KFM (Nm/kg)	1.91 ± 0.49	2.16 ± 0.48 [a]	2.32 ± 0.31 [a]
Peak KFM (Nm/kg/m)	1.40 ± 0.35	1.46 ± 0.35	1.40 ± 0.18
Peak KIRM (Nm/kg)	-0.13 ± 0.09	-0.14 ± 0.09	-0.16 ± 0.09
Peak KIRM (Nm/kg/m)	-0.09 ± 0.07	-0.10 ± 0.07	-0.10 ± 0.05

HAM at time of peak KAbM (Nm/kg)	-0.16 ± 0.33	-0.37 ± 0.46 [a]	-0.47 ± 0.40 [a]
HAM at time of peak KAbM (Nm/kg/m)	-0.11 ± 0.25	-0.25 ± 0.31 [a]	-0.28 ± 0.25 [a]
HFM at time of peak KFM (Nm/kg)	0.61 ± 0.36	0.53 ± 0.32	0.07 ± 0.41 [a,b]
HFM at time of peak KFM (Nm/kg/m)	0.44 ± 0.26	0.36 ± 0.22	0.04 ± 0.25 [a,b]

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[a] denotes significantly different to pre-pubertal group ($p<0.05$)

[b] denotes significantly different to early/mid-pubertal group ($p<0.05$)

5.5. DISCUSSION

This is the first study to investigate differences in running-related lower limb joint moments across key stages of female pubertal development. Girls in the latter stages of pubertal development ran with higher peak KFM normalised to body mass, but no differences were found when normalised to body mass by height, suggesting that increases in peak KFM compared to pre-pubertal girls are driven by changes in height. In addition, a lower HFM at time of peak KFM and HAM at time of peak KAbM compared to pre-pubertal girls was evident, irrespective of normalisation method. These results partly support the primary and secondary hypotheses of a higher peak KFM in late/post- compared to pre-pubertal girls for body mass normalised moments, and a higher peak KFM in early/mid- compared to pre-pubertal girls. However, the part of the hypothesis pertaining to between-group differences for peak KAbM and KIRM for body mass normalised data is rejected. Regarding the third hypothesis, this was also partially supported with *post-hoc* comparisons demonstrating a lower HFM at time of peak KFM (irrespective of normalisation method) in the late/post-pubertal group compared to early/mid- and pre-pubertal girls. By contrast, part of the third hypothesis of higher HAM at time of peak KAbM in more mature girls was not supported.

Higher peak KFM normalised to body mass and lower HFM at time of KFM for body mass and body mass by height normalisations in late/post-pubertal girls compared to their pre-pubertal counterparts is an important finding given that these variables produced large effect sizes (*d*= 1.01-1.42) and have been linked with the development of PFP (Teng et al. 2015, Neal et al. 2016). This provides further support to the contention that altered running strategies may develop during puberty that increase sagittal plane knee loads (Sigward et al. 2012). As discussed in detail in Study 1

(Chapter 3), pubertal-related growth, as evidenced by the longer thigh and shank segment lengths in our late/post-pubertal group, are likely contributors to their higher KFM. For example, longer segment lengths, in conjunction with maturational-driven increases in muscle mass and fat deposits (Faust 1977), can increase the muscular torque required to control the segmental motion of limbs during dynamic tasks such as running (Winter 2009). Given that the growth of long bones precedes increases in muscle strength and neuromuscular control (Tanner 1962, Faust 1977), a disproportionate increase in sagittal plane knee/hip moments can result.

Indeed, the finding of lower HFM at time of peak KFM in late/post-pubertal girls compared to pre-pubertal counterparts regardless of normalisation method is important and highly novel. Although trunk flexion angles were not investigated in the present study due to issues with participant clothing and gaps/errors tracking the T10 marker, evidence supports the relationship between trunk angles and hip/knee loading (Teng and Powers 2014, Teng and Powers 2015). In a study by Teng and Powers (2015), hip extensor energy generation and knee extensor energy absorption were investigated in a sample of 40 male and female runners divided into high trunk flexion (10.8 ± 2.2°) and low trunk flexion (3.6 ± 2.8°; (Teng and Powers 2015)). The group with higher trunk flexion angles simultaneously increased their hip extensor energy generation and lowered knee energy absorption compared to the low flexion group. Moreover, in a separate study by Teng and Powers (2014) investigating PFJ stress and trunk flexion angles in healthy recreational runners (*n*=24), those with higher trunk flexion angles had lower PFJ stress (Teng and Powers 2014), which is closely related to peak KFM (Bonacci et al. 2014). Hence, it may be that alterations in trunk flexion angles in the late/post-pubertal compared to pre-pubertal girls contribute to between-group differences in HFM at time of peak KFM and is a noteworthy variable to consider in future pubertal studies .

There were no between-group differences in KAbM, which is surprising given that previous landing-related research has shown post-pubertal girls exhibit higher KAbM compared to pre pubertal counterparts (Hewett et al. 2004, Ford et al. 2010), further supported by the findings reported in Chapter 3. Conflicting findings may be due to a lower HAM (i.e., higher hip abduction moment) at the time of peak KAbM in the late/post-pubertal girls compared to pre-pubertal girls in the present study that may be partly attributed to muscle activation patterns as previously discussed. More importantly, this study reported a moderate pubertal-related increase in the hip abduction moment at time of peak KAbM (*d*= 0.53-0.86) instead of a HAM during running, which may be a protective mechanism to ameliorate frontal plane peak KAbM. Support for this theory is highlighted by Ferber and colleagues (Ferber et al. 2010), in which running biomechanics of healthy adult females also exhibit a hip abduction moment during early stance (Novacheck 1998, Ferber et al. 2010). Considering the HAM in the present study was derived at time of peak KAbM, which typically occurs during early stance (Hewett et al. 2005), this may partly explain these findings.

Furthermore, differences in task demand between jumping tasks and running may further explain the discrepancy in findings relating to peak KAbM and KIRM. Whilst previous landing studies have reported pubertal-related differences in frontal plane moments (Hewett et al. 2004, Ford et al. 2010) and transverse plane kinematics (Kim and Lim 2014), landing from a jump requires higher lower limb multi-planar stability (Pappas et al. 2007), whereby large knee abduction and internal rotation forces are applied to the knee (Quatman et al. 2010). By contrast, running is predominantly a sagittal plane biased movement with minimal frontal or transverse plane forces (Novacheck 1998). Therefore, the selected task may also have contributed to the lack of differences in peak KAbM and KIRM amongst pubertal groups.

Whilst inferences about how these findings may relate to adolescent PFP can't be made, it is recommended that future studies investigate the role of peak KFM in the development of PFP, particularly as large effect sizes were found during puberty (*d*= 0.52-1.01). Given that previous studies have shown that higher peak KFM is a pathway to chondral deformation (Teng et al. 2015) and increased PFJ stress (Bonacci et al. 2014), higher peak KFM may ultimately contribute to overall PFP risk. Therefore, investigating female pubertal cohorts may be novel and provide further insights to this condition.

Although these findings are novel, this study has limitations. Firstly, a lack of *in vivo* PFJ loads and/or prospective study design, does not link higher peak KFM in healthy physically active pubertal girls to increased PFJ contact forces and ultimately increased risk of PFP. In addition, an absence of strength/neuromuscular data (e.g. electromyography or hip/knee isokinetic muscle strength) and trunk flexion angles, limit explanation of the mechanisms contributing to altered knee and hip moments. Finally, participants in this study ran barefoot which is unlikely to reflect every-day running behaviour, and is likely to alter knee moments compared to running in shoes (Bonacci et al. 2014). Future studies may consider examining the effects of footwear on lower extremity running biomechanics in girls throughout pubertal development.

5.6. CONCLUSION

Girls at latter stages of puberty exhibit higher sagittal, but not frontal or transverse plane knee moments while running barefoot. The higher sagittal knee moments are explained by increases in height rather than body mass. At the hip, a lower HFM at time of KFM and HAM at time of KAbM were found at the latter stages of development irrespective of normalisation method. Consequently, higher sagittal plane peak KFM and a lower HFM at time of peak KFM at latter stages of puberty may increase risk of knee injuries such as PFP given these variables are associated with higher PFJ stress.

CHAPTER 6

STUDY 4: *Differences and mechanisms underpinning a change in the knee flexion moment while running in high- and low-supportive footwear among young females*

6.1. CHAPTER OVERVIEW

This chapter examined differences in running-related peak KFM between footwear conditions (i.e., barefoot, high-support and low-support) amongst girls pooled across early/mid- and late/post-pubertal groups. Moreover, the biomechanical mechanisms behind a change in peak KFM between footwear conditions were explored to understand how footwear may influence this moment.

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6.2. INTRODUCTION

Running is a popular exercise associated with a healthy lifestyle. Despite the benefits of running, the repetitive nature of the task can lead to musculoskeletal injuries (Novacheck 1998 A), with PFP being one of the most common (Taunton et al. 2002). Specifically, a high incidence of PFP is reported amongst adolescent females with 15-30% developing the condition (Fairbank et al. 1984, Myer et al. 2010). and many experiencing recurrent symptoms into adulthood (Crossley et al. 2016).

Although the causes of PFP amongst adolescent females are multifactorial (Fulkerson and Arendt 2000, Lankhorst et al. 2013, Crossley et al. 2016), altered sagittal plane knee biomechanics, particularly a higher peak KFM, may increase patellofemoral joint loads and, in turn, increase the risk of developing PFP (Farrokhi et al. 2011, Bonacci et al. 2014). Higher peak KFMs may be driven by growth-related factors associated with female pubertal development (Faust 1977, Davies and Rose 2000, Wild et al. 2013). Indeed, Study 3 (Chapter 5) reported higher barefoot running-related peak KFM amongst late/post- and early/mid-pubertal girls compared to their pre-pubertal counterparts for body mass, rather than body mass by height normalised knee moments. Since height appears to be more influential on running-related peak KFM than body mass during puberty, and girls in the late/post- and early/mid-pubertal groups are likely at higher risk of PFP (Devereaux and Lachmann 1984, Fairbank et al. 1984, Novacheck 1998, Powers 2003), further mechanistic analysis of the peak KFM normalised to body mass in this cohort of young females is required.

More importantly, girls likely wear various types of athletic footwear while running which may further augment risk of developing PFP, as previous running studies in young male and female adults (mean ages = 29.2 ± 6 and 26.2 ± 5.5) have reported higher peak KFM when wearing high-supportive shoes (i.e., footwear with increased medial, midfoot and longitudinal stiffness) and low-supportive shoes (i.e., footwear with lower medial, midfoot and longitudinal stiffness) compared to barefoot (Bonacci et al. 2014, Sinclair 2014). While a direct comparison between shoes was not explored in these studies, the high-supportive shoes produced higher peak values compared to low-supportive shoes, indicating between footwear differences may also be evident while running. Interestingly, Study 2 (Chapter 4) explored the effect of high-support shoes, low-support shoes and barefoot on landing-related biomechanics in late/post-pubertal girls, also reporting a higher peak KFM wearing both types of shoes compared to barefoot; yet, no between shoe differences were found. That being said, the single limb landing task explored in Study 2 is vastly different from running and results cannot necessarily be generalized across the two tasks (Novacheck 1998). Furthermore, it is presently not clear how these types of footwear influence running biomechanics in young females. Therefore, it is important to determine whether running-related peak KFM differs between high-support shoes, low-support shoes and barefoot in an adolescent/young adult female cohort.

Although the literature, and findings from Study 2 (Chapter 4) suggest footwear increases peak KFM, the biomechanical mechanisms behind this effect are unknown. There has been no published investigation of the underlying mechanisms by which high- and low-support shoes may alter running-related peak KFM. Understanding mechanisms may help inform footwear manufacturers and researchers about future footwear design. Theoretically, footwear is thought to increase the peak KFM through a change in lower limb kinematics, likely through increased dorsiflexion and knee flexion angles compared to barefoot (Sinclair 2014). Increased knee flexion and ankle dorsiflexion wearing shoes (Sinclair 2014), may lead to a higher perpendicular distance (mm) from the knee joint centre (KJC) to GRF vector (i.e., the knee-GRF lever arm), resulting in higher peak KFM, although this mechanism is yet to be confirmed. Likewise, the sagittal plane resultant GRF magnitude may also be influenced by footwear (Rice et al. 2016), and thus may be another potential contributor to alterations in the peak KFM. Hence, lower limb kinematics, the knee-GRF lever arm and sagittal plane resultant GRF magnitude are likely relevant variables to explore as mechanisms underpinning a potential change in peak KFM between footwear conditions during running.

In light of these considerations, the primary aim of this study was to examine differences in running-related peak KFM between barefoot, high-support and low-support footwear of adolescent and young adult girls spanning early to post-puberty. If footwear-related differences for peak KFM were found, the secondary aim was to determine whether the knee-GRF lever arm, sagittal plane resultant GRF magnitude and sagittal-plane kinematics (i.e., hip flexion angle, knee flexion angle, ankle dorsiflexion angle all at time of peak KFM, in addition to knee flexion excursion and knee flexion angle at initial contact) were predictive of the change in peak KFM between footwear conditions. The primary hypothesis was that both the high- and low-support shoes would elevate peak KFM (normalised to body mass) compared to barefoot, but that the increase in peak KFM would be less with the low-supportive shoes.

6.3. METHODS

6.3.1. PARTICIPANTS

This was a nested cohort study based on the findings of Study 3 (Chapter 5) in which higher peak KFM was found during running in both early/mid- and late/post-pubertal groups compared to pre-pubertal girls, yet with no differences between early/mid- and late/post-pubertal groups. Moreover, no between group differences were reported for the peak KAbM or KIRM. Thus, this study included the 60 girls in the early/mid- and late/post-pubertal groups. This may provide more valuable information in the context of PFP as this population is generally at higher risk of this condition compared to pre-pubertal girls (Fairbank et al. 1984, Myer et al. 2010).

As described in Study 3 (Chapter 5), girls were recruited from local sporting clubs surrounding the University of Melbourne Parkville campus. All participants included were healthy, physically active girls with a healthy weight (i.e., BMI <30 kg/m^2). Girls were excluded if they: (i) had a history of lower limb injury, knee pain or medical condition that currently affected walking, running or jumping, (ii) previous ACL, meniscal or PFJ injury, (iii) use of a bi- or tri-phasic OCP, (iv) any medically prescribed or over the counter orthotic worn in the past 6 months and (v) unable to speak write or read English. Written informed consent was obtained from the participant or her parent/guardian with prior ethics approval from the University of Melbourne HEAG and HESC (application ID 1442604; Appendix 1).

Information regarding menarche was also used to determine the appropriate time for biomechanical testing as outlined in Study 3 (Chapter 5), as fluctuating estradiol levels may influence lower limb biomechanics (Wild et al. 2012, Balachandar et al. 2017). Girls who indicated that they had experienced menarche, but were not using a monophasic OCP were tested within the first 7 days of their menstrual cycle (i.e., early follicular phase). In contrast, girls who had not experienced menarche or were on a monophasic OCP were tested anytime. To ensure that all girls included were indeed tested at the time of low estradiol levels, a 5mL saliva sample was provided immediately before the running task. The sample was then sent to the manufacturer (Nutripath Integrative Pathology, Melbourne, Australia) for analysis via enzyme immunoassay. Estradiol results were required to be <18 pmol/L according to the reference ranges for the follicular phase provided by the manufacturer.

Descriptive measures of height and weight were recorded barefoot (see Section 3.3.7). Participants then completed the LPI to determine the dominant leg for analysis (see Section 3.3.9). Following this, 13mm retroreflective markers were adhered to each participant's trunk, thigh, shank and foot according to a model previously described by Schache and Baker (Section 3.3.8, Chapter 3; (Schache and Baker 2007).

6.3.2. RUNNING TASK

Participants were required to complete three successful running trials as per Study 3 (Chapter 5) in three different footwear conditions: i) barefoot, ii) low-support shoes and, iii) high-support shoes (Appendix 3). No instructions were given about running technique and each participant was given approximately five minutes to accustom herself to the running task. A successful trial involved (i) clean strike of force plate and (ii) running speed 2.8-3.2 m/s (measured via photoelectric timing gates). In the event a participant ran faster or slower than the designated time, she was instructed to adjust her speed accordingly until the correct speed was attained. In the same manner as the previous study (Chapter 5) and to ensure participants ran at the same speed in each footwear condition, running velocity was also calculated from the mid-point between the ASIS markers and averaged across three trials (see Section 5.3.2) and reported in m/s. The order of footwear condition for each participant was pre-determined via block randomization.

6.3.3. FOOTWEAR

High- and low-supportive shoes were classified according to the criteria outlined in Study 2 (Chapter 4; Section 4.3.2). Briefly, shoes were classified based on features outlined in the FAT such as medial, heel counter, midfoot and longitudinal shoe stiffness (Barton et al. 2009). Specifically, high-support shoes were required to possess: (i) a midsole that was denser medially than laterally (i.e., medial post), (ii) <10° midfoot frontal plane (torsional) stiffness, (iii) <10° heel counter stiffness and (iv) <45° midfoot sagittal plane (longitudinal) stability. In contrast, the low-support shoe was required to possess: (i) a uniform midsole density, (ii) 10-45° heel counter stiffness (iii) 10-45° torsional stiffness, (iv) >45° midfoot longitudinal stiffness. Based on these criteria, the Asics Kayano-GS was tested as the high-support shoe and the Asics Zaraca as the low-support shoe (Appendix 3). Further information regarding shoe mass, stack height and footwear pitch can be found in Section 4.3.2 and Appendix 3.

6.3.4. MOTION ANALYSIS

As per Study 3 (Chapter 3; Section 3.3.8), kinematic (120Hz) and GRF data (2400Hz) were collected using a 12-camera Vicon motion analysis system (Oxford, UK) synchronized with a concealed force plate (AMTI, Inc., Watertown, MA, USA).

Data were filtered using a fourth order zero-lag Butterworth low-pass filter with a cut-off frequency of 20 Hz. Joint moments were analysed across the whole stance phase using inverse dynamics and expressed in the distal anatomical reference frame normalised to body mass (Nm/kg; (Schache and Baker 2007), as this was a within group comparison of girls pooled across early/mid- and late/post-pubertal groups. Pooling was done based on the findings presented in Study 3 (Chapter 5), whereby no differences in peak knee moments between these groups were found, yet both groups had higher peak KFM compared to their pre-pubertal counterparts. All biomechanical variables described in this study are outlined in Table 6.1. The sagittal plane knee-GRF lever arm and the resultant sagittal plane GRF magnitude were both derived from a custom-written Body Builder program (Vicon, Oxford, UK) and averaged across three running trials. Descriptive data pertaining to the anthropometric segment lengths for the thigh and shank were derived and extracted from the kinematic model.

Table 6.1. **Biomechanical variables of interest between footwear conditions**.

Variable	Definition
Peak KFM (Nm/kg)	Peak external knee flexion moment during stance. Positive values indicate higher KFM.
Sagittal plane knee-GRF lever arm (mm)	Perpendicular distance between GRF and knee joint centre in laboratory sagittal plane. Calculated at time of peak KFM.
Sagittal plane resultant GRF magnitude (BW)	Resultant magnitude of the sagittal plane GRF calculated at time of peak KFM. Force was converted from Newton's to bodyweight (BW).
Knee flexion angle (°)	Sagittal plane knee flexion angle at time of peak KFM. Positive values indicate knee flexion.
Ankle dorsiflexion angle (°)	Sagittal plane ankle dorsiflexion angle at time of peak KFM. Positive values indicate dorsiflexion.
Hip flexion angle (°)	Sagittal plane hip flexion angle at time of peak KFM. Positive values indicate hip flexion.
Knee flexion excursion (°)	Difference between the knee flexion angle at initial contact and peak across stance phase.
Knee flexion at initial contact (°)	Knee flexion angle at initial contact of force plate. Initial contact designated as time when GRF >20 N.

6.3.5. STATISTICS

Descriptive data (i.e., means and SD) were calculated for all outcome variables. A repeated measures ANOVA was run to examine differences between footwear conditions (barefoot, high-support and low-support) for each biomechanical variable outlined in Table 6.1. In contrast to Study 2 (Chapter 4), FPI was not used as a covariate as it is more relevant to frontal and transverse plane biomechanics, rather than sagittal plane biomechanics (Loudon et al. 1996, Novacheck 1998, Hewett et al. 2005). In the event of a significant main effect of footwear condition, *post-hoc* analysis using Fisher's LSD tests were performed, whereby the MD, 95% CI and effect size (η_p^2 and Cohen's *d*) were reported for all significant variables in the same manner as previous Chapters.

Following this, if a significant difference in peak KFM between footwear (i.e., high- and low-support shoes) compared to barefoot was evident, a linear mixed model with a random intercept for participant was run to determine which variables are predictive of the change in peak KFM (i.e., dependent variable) wearing shoes compared to barefoot. Rather than run two separate regression models for high-support and low-support shoes compared to barefoot, footwear condition was entered as a fixed effect in the linear mixed model which determined if wearing the different shoes (i.e., high-support and low-support) are associated with a change in peak KFM with respect to barefoot. Furthermore, before running the mixed model, a preliminary step was taken in which the change in lower limb kinematics, change in sagittal plane knee-GRF lever arm and change in sagittal plane resultant GRF magnitude variables were run separately as interaction terms with footwear condition, to determine if high- and low-supportive shoes may have influenced these variables differently. If any interactions were identified, the change in this interaction term and the change in each predictor alone (Table 6.1) was included as a covariate (s) in the linear mixed model.

The fixed effect estimates, 95% CI and *p* values were reported. All data were analysed using the SPSS (version 23, IBM) and $p<0.05$ was used to indicate statistical significance.

6.4. RESULTS

Participant demographics are shown in Table 6.2. Included in the study were 29 pre-menarche girls, 20 eumenorrheic girls and 11 girls using the monophasic OCP. A mean value of 8.1 ± 5.1 pmol/L confirmed low estradiol levels at the time of testing (Table 6.2).

Differences in peak KFM, GRF and lower limb kinematics between footwear conditions

The ANOVA analysis revealed no differences in running velocity between footwear conditions ($p>0.05$). However, a main effect of footwear for peak KFM was found ($p<0.001$, $\eta_p^2= 0.75$). *Post-hoc* analysis revealed that the high-support (MD= 0.42, 95% CI= 0.36, 0.49 Nm/kg, $p<0.001$, $d=1.07$) and low-support (MD=0.38, 95% CI= 0.31, 0.45 Nm/kg, $p<0.001$, $d=0.97$, Table 6.3) shoes resulted in a higher peak KFM during running compared to barefoot. No differences in the peak KFM between shoes were found ($p>0.05$).

Similarly, main effects of footwear were found for all remaining variables outlined in Table 6.3. *Post-hoc* comparisons revealed a higher knee-GRF lever arm wearing high support shoes compared to low-support (MD= 2.23, 95% CI= 0.11, 4.30 mm, *p*= 0.039, *d*= 0.13) and barefoot conditions (MD= 15.75, 95% CI= 13.41, 18.08 mm, *p*<0.001, *d*= 0.88). Furthermore, the low-support shoes increased the knee-GRF lever arm compared to barefoot (MD= 13.54, 95% CI= 11.06, 16.02 mm, *p* <0.001, *d*= 0.78). Regarding the sagittal plane resultant GRF magnitude, wearing both high-supportive shoes (MD= 0.07, 95% CI= 0.03, 0.10 BW, *p*<0.001, *d*= 0.16), and low-support shoes (MD= 0.08, 95% CI= 0.05, 0.11, *p*<0.001, *d*= 0.18) increased compared to barefoot, yet no differences were found between shoe conditions (*p*>0.05).

In relation to lower limb kinematics, the knee flexion angle at peak KFM in high-support (MD= 2.03, 95% CI= 1.16, 2.90 °, *p*<0.001, *d*= 0.44) and low-support shoes (MD= 2.41, 95% CI= 1.76, 3.04 °, *p*<0.001, *d*= 0.56) was elevated compared to barefoot, with no between shoe differences (*p*>0.05). For the ankle dorsiflexion angle at peak KFM, the high-support shoe significantly increased this parameter compared to barefoot (MD= 1.16, 95% CI= 0.33, 2.00 °, *p*=0.007, *d*= 0.34), yet no differences were found wearing low-support shoes compared to high-support or barefoot conditions (*p*>0.05). At the hip, the high-supportive shoes (MD= 2.81, 95% CI= 1.79, 3.82 °, *p*<0.001, *d*= 0.36) and low-supportive shoes (MD= 2.40, 95% CI= 1.52, 3.28°, *p*<0.001, *d*= 0.32) increased the flexion angle at peak KFM compared to barefoot, with no between shoe differences evident (*p*>0.05).

Differences between footwear and barefoot were also evident for knee excursion angle across the stance phase with higher values wearing high-support (MD= 3.82, 95% CI= 2.99, 4.65 °, *p*<0.001, *d*= 0.85) and low-support shoes (MD= 3.92, 95% CI= 3.19, 4.64 °, *p*<0.001, *d*= 0.86) compared to barefoot. Surprisingly, knee flexion angle at initial contact was lower in high-supportive shoes compared to low-supportive shoes (MD= 1.48, 95% CI= 0.07, 2.90 °, *p*=0.04, *d*= 0.68) and barefoot (MD= 2.95, 95% CI= 1.96, 3.95 °, *p*<0.001, *d*=0.68), with the low-support shoe revealing lower angles at initial contact compared to barefoot (MD= 1.47, 95% CI= 0.25, 2.70, *p*=0.019, *d*= 0.29).

Table 6.2. Participant characteristics. All variables are reported as mean ± SD.

Variable	Sample (*n*=60)
Age (years)	15.6 ± 5.4
Weight (kg)	49.6 ± 13.8
Height (m)	1.6 ± 0.1
Estradiol (pmol/L)	8.1 ± 5.1
Thigh segment length (cm)	41.2 ± 3.5
Shank segment length (cm)	36.8 ± 3.2

Table 6.3. Differences in biomechanical variables of interest between footwear conditions. All variables are reported as mean ± SD.

Variable	Barefoot	High-support	Low-support
Peak KFM (Nm/kg)	2.24 ± 0.41	2.67 ± 0.41[a]	2.62 ± 0.39 [a]
Running velocity (m/s)	3.12 ± 0.20	3.12 ± 0.21	3.14 ± 0.21
Sagittal plane knee-GRF lever arm (mm)*	103.75 ± 18.05	119.50 ± 18.04 [ab]	117.29 ± 17.05 [a]
Sagittal plane resultant GRF magnitude (BW)*	2.48 ± 0.45	2.55 ± 0.44 [a]	2.56 ± 0.44 [a]
Hip flexion angle (°)*	37.64 ± 7.60	40.45 ± 8.04 [a]	40.04 ± 7.58 [a]
Knee flexion angle (°)*	46.96 ± 4.52	48.99 ± 4.84 [a]	49.36 ± 4.10 [a]
Knee flexion at initial contact (°)	19.11 ± 4.30	16.16 ± 4.40 [ab]	17.64 ± 5.83 [a]
Knee flexion excursion (°)	32.40 ± 4.79	36.21 ± 4.22 [a]	36.31 ± 4.32 [a]
Ankle dorsiflexion angle (°)*	19.01 ± 3.81	20.17 ± 3.08 [a]	19.75 ± 3.37

* at time of peak KFM

a significantly different to barefoot

b significantly different to low-support

Mechanisms underlying a change in peak KFM between footwear and barefoot

An interaction was identified between footwear condition and the change in knee-GRF lever arm ($F_{(2,\ 117)}$= 79.38, $p<0.001$). Subsequently, this interaction term was included in the regression model analysing predictors of a change in peak KFM between footwear and barefoot conditions. This model included a total of nine potential predictors (Table 6.4). However, only the change in knee-GRF lever arm was predictive of a change in peak KFM ($F_{(1,\ 109)}$= 93.56, $p<0.001$, Table 4), whereas the change in sagittal-plane resultant GRF magnitude, footwear condition and its interaction, and change in hip, knee and ankle kinematics were not related to a change in peak KFM ($p>0.05$, Table 6.4).

Table 6.4. Linear mixed model analysis for the change in peak KFM between footwear and barefoot conditions. Fixed effect estimates, 95%CI and *p* values are reported for each term analysed within the model.

Predictors	Change in Peak KFM Fixed effect estimates, (95% CI), *p*-value
Footwear condition	0.04, (-0.10, 0.18), *p*=0.55
Change in sagittal plane knee-GRF lever arm (mm)	0.02, (0.02, 0.03), *p*<0.001
Change in sagittal plane resultant GRF magnitude (BW)	-0.01, (-0.06, 0.04), *p*=0.72
Footwear condition*change in sagittal plane knee-GRF lever arm	0.00#, (-0.01, 0.01), *p*=0.65
Change in hip flexion angle (°)	-0.00#, (-0.02, 0.01), *p*=0.46
Change in knee flexion angle (°)	0.01, (-0.00#, 0.03), *p*=0.07
Change in knee flexion at initial contact (°)	-0.00#, (-0.01, 0.01), *p*=0.96
Change in knee flexion excursion (°)	0.00#, (-0.01, 0.03), *p*=0.64
Change in ankle dorsiflexion angle (°)	-0.00#, (-0.01, 0.01), *p*=0.97

# Indicates value below three decimal places

6.5. DISCUSSION

Running is a popular form of exercise amongst adolescent and young adult females who typically wear various types of athletic footwear when participating. This study reports higher running-related peak KFM whilst wearing commercially available high- and low-support shoes compared to barefoot, with no between shoe differences observed. Furthermore, a novel finding was the underlying mechanism by which footwear changes peak KFM compared to barefoot. The results showed that both shoes changed peak KFM via a change in the knee-GRF lever arm, rather than a change in the sagittal plane resultant GRF magnitude or changes in lower limb kinematics.

Higher running-related peak KFM in adolescent/young adult girls wearing shoes compared to barefoot partly supports the primary hypotheses of higher peak KFM wearing shoes compared to barefoot, yet rejects the hypothesis that a between shoe difference would exist. Increased running-related peak KFM wearing both high- and low-support shoes has previously been reported by Bonacci et al. (2014) and Sinclair (2014) amongst mixed adult cohorts aged 26-29 years (Bonacci et al. 2014, Sinclair 2014). The present study now extends these results to adolescent/young adult females and is the first to include a direct comparison of high and low-supportive shoes. The lack of between shoe differences in peak KFM suggests that the specific shoe design features (i.e., medial, midfoot and longitudinal shoe stiffness, Appendix 3) used to classify the shoes in this study into high or low supportive shoes may not influence the KFM. Clinically, irrespective of shoe type, a large effect size was evident (d=0.90-1.07) for peak KFM whilst shod compared to barefoot. As higher peak KFM is associated with PFJ stress and PFP (Farrokhi et al. 2011, Bonacci et al. 2014, Sinclair 2014), these shoe types may not be ideal for adolescent females.

The mechanism by which both shoes increased peak KFM compared to barefoot was via a change in the knee-GRF lever arm. Surprisingly, changes in lower limb kinematics or the sagittal plane resultant GRF magnitude were not independent predictors of a change in peak KFM. This is a novel finding indicating that future footwear modifications which aim to attenuate peak KFM may consider shoe design features that have the potential to reduce the knee-GRF lever arm.

Specifically, footwear pitch may be an important feature that influences the KFM as both the high- and low supportive shoes had a higher pitch (13mm and 10mm heel to toe offsets respectively; Appendix 3) compared to 0mm while barefoot. Although no studies have examined the relationship between pitch and change in peak KFM or the knee-GRF lever arm, lowering the pitch of shoes may influence these parameters by reducing ankle dorsiflexion and knee flexion angles towards barefoot levels. Support for this theory is highlighted by Lindenberg et al. (2011), in which the effect of heel height and knee flexion angle amongst collegiate females was explored during a forward hopping task (Lindenberg et al. 2011). This study found that increasing the heel pitch from 0 mm to 24 mm, significantly increased the peak knee flexion angle. Moreover, a study by Chambon et al. (2015) found that wearing shoes with 0, 4 and 8mm pitches reduced ankle dorsiflexion and increased knee flexion angle excursions while running over ground (Chambon et al. 2015). Combined, these studies support the notion that footwear pitch may be an important factor driving changes in peak KFM and/or the knee-GRF lever arm.

In contrast, a randomized controlled trial by Malisoux et al. (2017) reported the effect of 0, 6 and 10 mm pitch shoes on kinematics over a six month timeframe finding no between-shoe differences for mid-stance knee flexion angle (Malisoux et al. 2017). However, the knee flexion angle decreased in all shoe conditions over the follow-up period. Despite these contradictory findings, it is important to note that these studies did not evaluate knee joint moments, therefore it is plausible that footwear pitch may have influenced the peak KFM and the knee-GRF lever arm. Hence, future mechanistic studies are required to confirm the relationship between footwear pitch and these variables.

The repeated measures ANOVA also found higher hip, knee and ankle flexion angles at time of peak KFM in shoes compared to barefoot. Numerous other studies support these findings in both high- and/or low-supportive footwear (Bonacci et al. 2014, Sinclair 2014, Sinclair et al. 2016, Nigg et al. 2017). Although not relevant in explaining the increase in peak KFM with footwear, these kinematic alterations are still of relevance in the context of PFP given that recent systematic reviews report kinematic differences at the knee and ankle between individuals with and without PFP whilst wearing similar footwear styles (Barton et al. 2009, Lankhorst et al. 2013, Crossley et al. 2016). Knowing that high- and low-supportive footwear generally increases knee and ankle kinematics associated with the development of PFP, prescription of lower profile shoes (i.e., shoes with lower pitch) to adolescent females may help prevent the condition.

Although the mechanism by which footwear changed the knee-GRF lever arm was not explored, running-related spatiotemporal variables may be important to include in future studies. Specifically, examining the association between change in stride length and the change in the knee-GRF lever arm between footwear conditions is suggested based on recent evidence demonstrating footwear-related effects on stride length and peak KFM (Thompson et al. 2014, Sinclair et al. 2016). Additional support for this mechanism is provided by Sinclair and colleagues (2016) who revealed that high-supportive shoes not only increased peak KFM, but also increased stride length in comparison to barefoot-inspired shoes. While this suggests that stride length could indeed be related to the knee-GRF lever arm, which primarily dictates peak KFM, further investigation is required.

This study has a number of limitations. It examined a healthy adolescent/young adult female cohort free of PFP, thus no link can be made between footwear-related peak KFM and the risk of developing the condition. Further, prospective research would be needed to determine causality. In addition, the fact that only external moments and kinematic predictors of a change in peak KFM were included in this study is a limitation, as there are likely other variables associated with a change in the peak KFM that were not explored. For instance, alterations in internal forces provided by muscle, tendon or ligaments were not considered while wearing footwear. This is important as the proportion of external forces (i.e., peak KFM) compared to internal forces (i.e., quadriceps muscle forces) is susceptible to fluctuations during dynamic tasks such as running (Saxby et al. 2016). This notion is nicely outlined by Saxby and colleagues (2016), whereby the contribution of external and internal knee forces changed based on neuromuscular demand (i.e., walking compared to running). Hence, it is plausible that external and internal forces also change based on footwear condition. This highlights the importance of considering internal forces in future mechanistic footwear studies. As there is no gold standard/consistent method of characterizing high- and low-supportive footwear, this study utilised the FAT to appraise footwear characteristics provided by the manufacturer (i.e., medial post) or subjectively assessed by the candidate (i.e., torsional, longitudinal and heel counter stiffness, (Barton et al. 2009). Therefore, shoes used in the present study may not necessarily be classified as ‘high and ‘low’ support if additional features are chosen or other methods are utilized to characterize footwear type. Furthermore, only one particular brand of shoes was assessed and findings may not necessarily generalize to other brands of footwear.

6.6. CONCLUSION

This study found that running in commercially available high- and low-support shoes increased the peak KFM in adolescent/young adult girls compared to barefoot. Interestingly, there were no differences in peak KFM between the two footwear types. An increase in peak KFM wearing shoes was related to an increase in knee-GRF lever arm, but not to changes in the sagittal-plane resultant GRF magnitude or sagittal plane hip, knee or ankle kinematics. Future studies might consider modifying footwear features to attenuate these higher knee loads in young females given that higher peak KFM may be associated with a greater risk of developing pathological conditions such as PFP.

CHAPTER 7

Summary, strengths, limitations and future directions

7.1. SUMMARY OF FINDINGS

This thesis incorporated a series of cross-sectional studies that explored the effect of female pubertal development on tri-planar knee biomechanics during single-limb landing and running tasks associated with traumatic and overuse type knee injuries. In addition, the effect of commercially available high- and low-supportive athletic footwear was explored in adolescent females at the latter stages of puberty to determine if footwear provides a feasible approach for ameliorating higher knee moments associated with these knee injuries.

In Study 1, barefoot landing-related tri-planar knee and bi-planar hip moments of pre-, early/mid- and late/post-pubertal girls were explored normalised to body mass and body mass by height. A developmental increase in body mass, rather than body mass by height normalised moments from all three knee planes was found, whereby the late/post-pubertal girls demonstrated a higher peak KAbM (95% CI= -0.02, -0.17 Nm/kg, p=0.015, d=0.61), peak KFM (95% CI= 0.19, 0.68 Nm/kg, p=0.001, d=1.12) and peak KIRM (95% CI= -0.12, -0.03 Nm/kg, p=0.009, d=0.82) compared to pre-pubertal girls. No differences were observed in frontal or sagittal plane hip moments at the time of knee moments. These findings extend previous pubertal single-limb landing studies (Hass et al. 2003, Hass et al. 2005, Kim and Lim 2014), providing evidence that adolescent height, rather than body mass is an important factor influencing higher knee moments at the latter stages of puberty. Consequently, further research into the relationship between tri-planar knee moments, adolescent height and ACL injury is advocated.

Based on the findings of Study 1 (Chapter 3), the aim of Study 2 (Chapter 4) was to determine if footwear (i.e., high-support and low-support shoes) lowered higher barefoot knee moments amongst late/post-pubertal girls normalised to body mass. Moreover, as foot posture may have influenced the resultant knee moments between footwear conditions, a repeated measures ANOVA and ANCOVA with static foot posture as a covariate (as assessed using the FPI) was conducted. Results revealed no differences for peak KAbM or KIRM; however, a main effect for adjusted and unadjusted models for body mass ($p<0.001$). *Post-hoc* results revealed that the high-support (95% CI= 0.36, 0.53 Nm/kg, $p<0.001$, d= 1.11,) and low-support shoes had higher peak KFM (95% CI= 0.25, 0.48 Nm/kg, $p<0.001$, d= 0.85) than barefoot, yet no differences were observed between shoe conditions. These findings suggest that features within the high-supportive shoes are inadequate at reducing higher landing-related knee moments and offer no advantage compared to low-supportive shoes. In fact, both shoes increased sagittal plane knee load compared to barefoot landing, which is concerning in the context of ACL injury prevention.

The barefoot running-related effect of puberty on tri-planar knee moments and bi-planar hip moments was explored in Study 3 (Chapter 5). No previous study has examined these running-related biomechanical variables associated with overuse injuries (e.g. PFP) across the stages of female pubertal development. Higher peak KFM normalised to body mass was found in the late/post-pubertal (95% CI= 0.18 to 0.63 Nm/kg, $p=0.001$, d= 1.01) and early/mid-pubertal (95% CI= 0.02, 0.47 Nm/kg, $p=0.034$, d= 0.52) girls compared to the pre-pubertal girls; yet, no differences were found when normalised to body mass by height ($p>0.05$). Furthermore, no differences were found for body mass or body mass by height normalised peak KAbM or KIRM ($p>0.05$). Interestingly, peak KAbM and KFM results may have been driven by altered hip moments. Specifically, lower body mass normalised HAM at time of peak KFM (i.e., greater hip abduction moments) was found in the late/post- (95% CI= -0.51, -0.11 Nm/kg, $p=0.003$, $d= 0.86$) and early/mid-pubertal (95% CI= -0.42, -0.01 Nm/kg, $p=0.039$, $d= 0.53$) girls compared to their pre-pubertal counterparts. Similarly, in the sagittal plane, a developmental decrease in the HFM at time of peak KFM normalised to body mass was evident with the late/post-pubertal girls displaying lower HFM (95% CI= 0.65, 0.28 Nm/kg, $p<0.001$, $d=1.27$) compared to their early/mid- and pre-pubertal counterparts (95% CI= 0.36, 0.73 Nm/kg, $p<0.001$, $d=1.42$). Similar developmental differences in hip moments at peak knee moments were also found when normalised to body mass by height ($p<0.05$). This study also highlights that adolescent height at latter stages of puberty contributes to higher peak KFM while running, which may be further influenced by a lower HFM at time peak KFM. In contrast, a developmental decrease in HAM at peak KAbM may have contributed to a lack of between pubertal group differences in peak KAbM normalised to body mass. Given that higher peak KFM may ultimately contribute to higher PFJ loads, girls in at latter stages of puberty may be at greater risk of PFP.

Finally, based on the higher barefoot running-related peak KFM in early/mid- and late/post-pubertal girls, Study 4 (Chapter 6) pooled data from these groups to determine whether low- and high-support footwear influenced peak KFM. Furthermore, the biomechanical mechanism underlying change in peak KFM between footwear conditions was explored. A main effect ($p<0.001$) for peak KFM was found, with *post-*

hoc tests revealing both high- (95% CI= 0.36, 0.49 Nm/kg, $p<0.001$, $d=1.07$) and low-support (95% CI= 0.31, 0.45 Nm/kg, $p<0.001$, $d=0.97$) footwear increased peak KFM compared to barefoot. Similar effects were found for kinematics (hip flexion, knee flexion and ankle dorsiflexion angles), the knee-GRF lever arm and the sagittal plane resultant GRF magnitude at time of peak KFM. Biomechanical mechanisms associated with the change in peak KFM wearing shoes compared to barefoot was also explored using a regression model and identified that a change in the knee-GRF lever arm was associated with a change in peak KFM ($F_{(1,\ 109)}= 93.56$, $p<0.001$), but not the sagittal plane GRF magnitude or any lower limb kinematics ($p>0.05$). These findings extend previous reports in other cohorts that have reported higher peak KFMs wearing both high- and low-support footwear compared to barefoot (Bonacci et al. 2014, Sinclair 2014). Higher sagittal plane knee loads may increase the risk of PFP and based on this study, these athletic footwear styles may not be optimal for reducing potentially injurious knee loads in adolescent females. However, a novel finding from this study was a change in the knee-GRF lever arm associated with the change in peak KFM wearing shoes compared to barefoot. Therefore, lowering the peak KFM may be possible in future footwear studies by modifying footwear design features to reduce the knee-GRF lever arm.

7.2. STRENGTHS

There are several noteworthy strengths of this thesis. These include:

1. A series of novel studies investigating the effects of female pubertal development and athletic footwear on external knee and hip moments associated

with acute and chronic knee injuries. Given the lack of current studies describing the differences in knee and hip moments between pubertal phases, these findings provide a possible mechanistic explanation for higher rates of knee injury amongst pubertal girls, justifying future pubertal research projects.

2. Primary classification of pubertal stages was performed using the Tanner stages of breast development. Validity and reliability of Tanner stages were arguably enhanced given that parents/guardians of daughters <12 years old and participants >12 years old performed the ratings (Section 2.3.3, Chapter 2). Furthermore, including PHV and menarche as additional criteria for the early/mid- and late/post-pubertal phases further strengthened the classification system, particularly as these characteristics have been cited as important pubertal factors related to external knee moments (Wild et al. 2012, Hewett et al. 2015, Wild et al. 2016).

3. In contrast to previous pubertal single limb landing studies (Hass et al. 2003, Hass et al. 2005, Kim and Lim 2014, Wild et al. 2016) that have recruited relatively small sample sizes (i.e., 22-33 participants), the present study recruited 93 girls, with 31 girls in each pubertal group, improving the quality and power of results reported in this thesis.

4. Testing girls when estradiol levels were consistently low (i.e., follicular phase of the menstrual cycle) was important given that variable estradiol levels amongst participants could have influenced lower limb biomechanics and acted as a confounding variable within our studies (Wild et al. 2012, Balachandar et al. 2017). Specifically, ensuring each girl had estradiol saliva levels <18 pmol/L

minimised the influence of circulating estradiol concentrations across pubertal groups and, in turn, improved the rigour of biomechanical findings.

5. Finally, the findings of Study 4 (Chapter 6) were particularly novel, as no studies to date have explored the underlying mechanism associated with a change in peak KFM while running in different types of athletic shoes. Ultimately, understanding which factors drive changes in peak KFM whilst wearing athletic shoes is crucial for designing more efficacious footwear to lower sagittal plane knee loads.

7.3. LIMITATIONS

Specific limitations have been addressed in each study. However, general limitations pertaining to the studies outlined in this thesis include:

1. The cross-sectional nature of all studies does not allow exploration into the predictive capacity of higher knee moments in adolescent females and increased risk of ACL rupture or PFP.
2. Internal muscle and joint contact forces from neuro-musculoskeletal computational models (Saxby et al. 2016, Saxby et al. 2016 A), maximal and sub-maximal muscle strength (Barber-Westin et al. 2006) and knee/hip muscle force control (Perraton et al. 2017) were outside the scope of this thesis but are likely important factors to examine in future studies of pubertal biomechanics.
3. Regarding specific footwear limitations, an attempt was made to classify footwear based on features outlined in the FAT (Barton et al. 2009), since there is currently no consensus for the definition of high- and low-support athletic

footwear. Whilst it is contended that the features used to classify high- and low-support shoes in this thesis are reasonable, additional features such as footwear pitch or weight that were not included may provide different results.

4. Despite the shoes in this thesis having similar features to other footwear brands, the fact that only one footwear brand (i.e., Asics) was tested does not allow results to be generalized across all footwear brands.
5. FPI was explored in Study 2 to determine if static foot posture had any influence on tri-planar knee moments whilst wearing different types of shoes. The fact that FPI did not have an effect, does not indicate whether different types of footwear may have a more pronounced influence on pronated compared to supinated foot types. Therefore, future studies may consider examining the effect of high- and low-support shoes across FPI sub-types.
6. Finally, trunk biomechanics were not investigated in this thesis. Previous studies have demonstrated that trunk flexion angles can influence sagittal plane hip and knee loads (Teng and Powers 2014, Teng and Powers 2015). Moreover, in the frontal plane, a higher lateral trunk lean leads to a lateral shift in the GRF and a larger knee abduction angle that subsequently contributes to ACL rupture amongst females (Hewett 2009). Therefore, several findings presented in this thesis may have been influenced by differences in trunk flexion/lateral lean angles between pubertal groups. Future studies should consider examining the influence of trunk biomechanics on lower limb kinetics across pubertal stages.

7.4. FUTURE DIRECTIONS

Recommendations for future research have been discussed in each study throughout this thesis. Essentially, it is imperative that prospective analysis of girls in early/mid- and late/post-pubertal groups is performed to ascertain if higher landing-related tri-planar knee moments and running-related sagittal plane peak KFM directly increases the risk of non-contact ACL injury and PFP.

Perhaps more importantly, the fact that both high- and low-supportive footwear had no influence on frontal or transverse plane knee moments, but increased sagittal plane knee load during landing and running-related tasks, highlights the need for additional research into footwear characteristics that may be able to reduce these potentially injurious forces. Specifically, exploring whether modifications to heel height (i.e., pitch) and medial arch support (i.e., increase stiffness or height) improves knee biomechanics (i.e., lowers tri-planar knee moments) during dynamic tasks is required to elucidate whether footwear represents an effective injury prevention tool. Finally, it may also be worth exploring the effects of footwear amongst pre-pubertal girls, as higher landing and running-related peak KFMs wearing shoes compared to barefoot may increase knee injury risk as these girls commence puberty.

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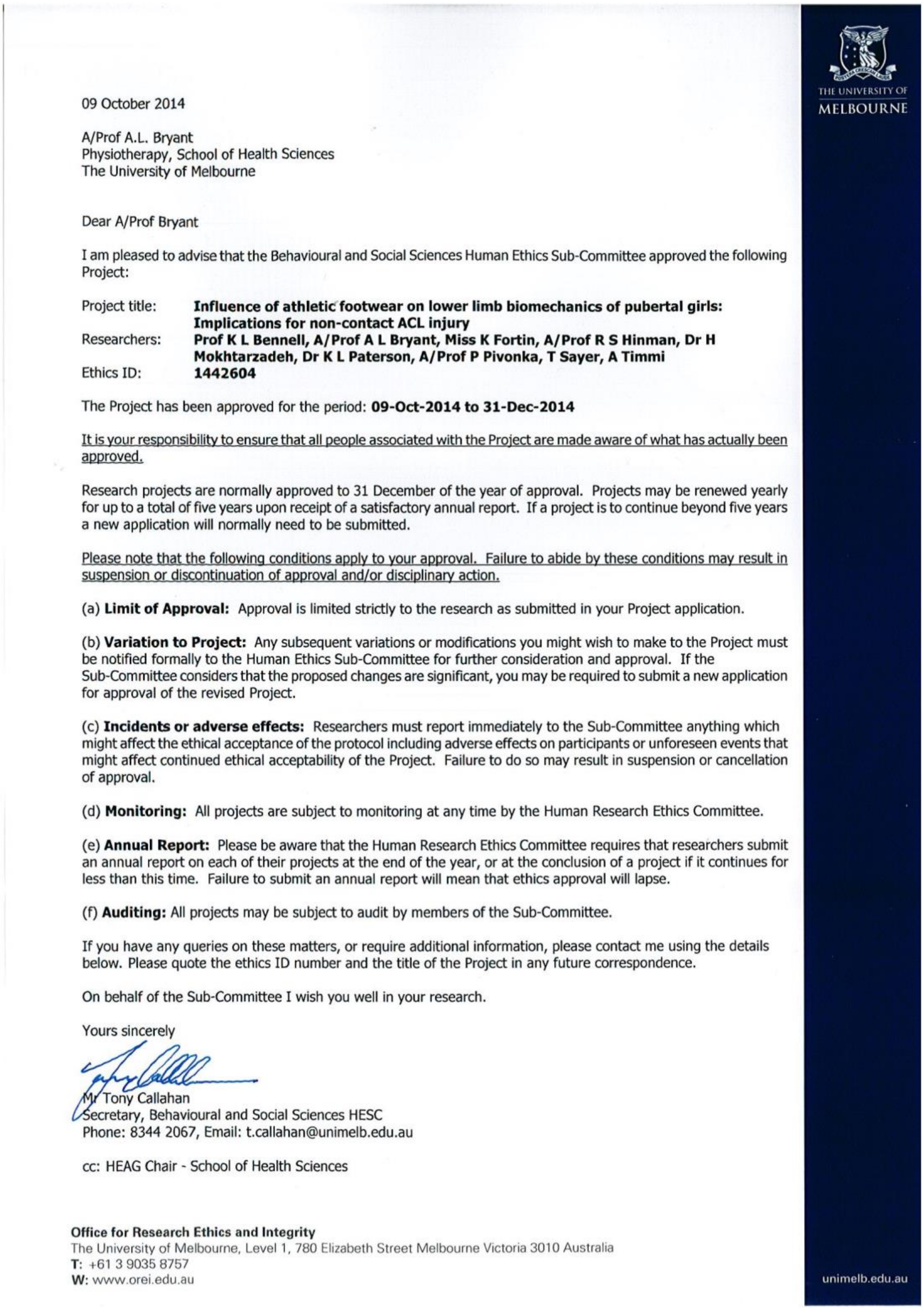
APPENDICES

1. Human ethics approval letter
2. Motion analysis marker placement
3. Footwear classification

APPENDIX 1

ETHICS APPROVAL



THE UNIVERSITY OF
MELBOURNE

09 October 2014

A/Prof A.L. Bryant
Physiotherapy, School of Health Sciences
The University of Melbourne

Dear A/Prof Bryant

I am pleased to advise that the Behavioural and Social Sciences Human Ethics Sub-Committee approved the following Project:

Project title:	**Influence of athletic footwear on lower limb biomechanics of pubertal girls: Implications for non-contact ACL injury**
Researchers:	**Prof K L Bennell, A/Prof A L Bryant, Miss K Fortin, A/Prof R S Hinman, Dr H Mokhtarzadeh, Dr K L Paterson, A/Prof P Pivonka, T Sayer, A Timmi**
Ethics ID:	**1442604**

The Project has been approved for the period: **09-Oct-2014 to 31-Dec-2014**

It is your responsibility to ensure that all people associated with the Project are made aware of what has actually been approved.

Research projects are normally approved to 31 December of the year of approval. Projects may be renewed yearly for up to a total of five years upon receipt of a satisfactory annual report. If a project is to continue beyond five years a new application will normally need to be submitted.

Please note that the following conditions apply to your approval. Failure to abide by these conditions may result in suspension or discontinuation of approval and/or disciplinary action.

(a) **Limit of Approval:** Approval is limited strictly to the research as submitted in your Project application.

(b) **Variation to Project:** Any subsequent variations or modifications you might wish to make to the Project must be notified formally to the Human Ethics Sub-Committee for further consideration and approval. If the Sub-Committee considers that the proposed changes are significant, you may be required to submit a new application for approval of the revised Project.

(c) **Incidents or adverse effects:** Researchers must report immediately to the Sub-Committee anything which might affect the ethical acceptance of the protocol including adverse effects on participants or unforeseen events that might affect continued ethical acceptability of the Project. Failure to do so may result in suspension or cancellation of approval.

(d) **Monitoring:** All projects are subject to monitoring at any time by the Human Research Ethics Committee.

(e) **Annual Report:** Please be aware that the Human Research Ethics Committee requires that researchers submit an annual report on each of their projects at the end of the year, or at the conclusion of a project if it continues for less than this time. Failure to submit an annual report will mean that ethics approval will lapse.

(f) **Auditing:** All projects may be subject to audit by members of the Sub-Committee.

If you have any queries on these matters, or require additional information, please contact me using the details below. Please quote the ethics ID number and the title of the Project in any future correspondence.

On behalf of the Sub-Committee I wish you well in your research.

Yours sincerely

Mr Tony Callahan
Secretary, Behavioural and Social Sciences HESC
Phone: 8344 2067, Email: t.callahan@unimelb.edu.au

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APPENDIX 2

MOTION ANALYSIS MARKER PLACEMENT

Marker (13mm)	**Description**	**Static calibration only (*)**
Trunk		
Man	Jugular notch	
T2	2nd thoracic vertebrae	
T10	10th thoracic vertebrae	
Pelvis		
LASIS/RASIS	Anterior superior iliac spine (ASIS)	
SACR	Midpoint between left and right posterior superior iliac spine (PSIS)	
Thigh		
LTHAP/RTHAP	Proximal anterior thigh	
LTHAD/RTHAD	Distal anterior thigh	
LTHLP/RTHLP	Proximal lateral thigh	
LTHLD/RTHLD	Distal lateral thigh	
LLEPI/RLEPI	Lateral epicondyle of knee	
LMEPI/RMEPI	Medial epicondyle of knee	*
RPAT/LPAT	Patella	
Tibia		
LTIAP/RTIAP	Proximal anterior tibia (1/3 from lateral epicondyle to lateral malleolus)	
LTIAD/LTIAD	Distal anterior tibia (2/3 from lateral epicondyle to lateral malleolus)	
LTILAT/RTILAT	Lateral tibia (1/2 from lateral epicondyle to lateral malleolus)	
LLMAL/RLMAL	Lateral malleolus	
LMMAL/RMMAL	Medial malleolus	*
Foot		
LHEEL/RHEEL	Distal calcaneus	
LHEEL2/RHEEL2	Proximal calcaneus	*
LMFS/RMFS	Midfoot superior	
LMFL/RMFL	Midfoot lateral	
RTOE/LTOE	Junction between 2nd and 3rd metatarsophalangeal (MTP) joint	*

APPENDIX 3

FOOTWEAR

The high-support shoe (A) was an Asics Kayano-GS model. Medial stiffness was ascertained from the medial post, which is located within the midsole of the shoe and provided medial foot support. The grey plastic region known as the Trusstic is a unique feature manufactured by Asics, depicted in the diagram below. The Trusstic provides a structural support feature to increase torsional stiffness and longitudinal shoe stability.

A

High-support footwear features
Medial post
<10° torsional stiffness
<10° heel counter stiffness
<45° midfoot longitudinal stability

Additional characteristics	
Stack height	Heel- 25 mm Forefoot- 12 mm
Heel to toe offset (i.e. pitch)	13 mm
Shoe mass	260 g

The additional characteristics provided above are based on a size 7 children's shoe, equivalent to a size 8.5 US womens.

The low-support shoe (B) was an Asics Zaraca 3 model, which was more flexible and allowed greater torsional and longitudinal movement (i.e., lower stiffness). The medial and lateral side of the shoe was equal (i.e., no medial post). Regarding the heel counter, this feature had greater heel movement than the high-support shoe when clasped in the frontal plane. The heel counter is not pictured below but lies within the upper sole of the rearfoot, clasping the calcaneus.

B

Low-support footwear features
Uniform midsole density
10-45° torsional stiffness
10-45° heel counter stiffness
>45° midfoot longitudinal stability

Additional characteristics	
Stack height	Heel- 28 mm Forefoot- 18 mm
Heel to toe offset (i.e. pitch)	10 mm
Shoe mass	240 g

The additional characteristics provided above are based on a size 7 children's shoe, equivalent to a size 8.5 US womens.