

STIFFNESS DURING SUB-MAXIMAL HOPPING AND SPRINTING IN YOUTH FEMALE ATHLETES

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TABLE OF CONTENTS

Abstract	vii
List of figures	ix
List of tables	x
List of common abbreviations	xi
Attestation of authorship	xvi
Co-Authored works	xvii
Acknowledgements.....	xix
Chapter 1. Introduction.....	1
1.1 Background	1
1.2 Thesis rationale	5
1.3 Aims/Objectives	6
1.4 Project context	7
1.5 Originality, significance, rigor	8
1.5.1 Originality.....	8
1.5.2 Significance	10
1.5.3 Rigor	11
1.6 Thesis structure.....	12
Chapter 2. A literature review on multi-level stiffness behavior in young female athletes.....	14
2.0 Prelude	14
2.1 Introduction	14
2.2 The structure and behaviour of global and intrinsic stiffness.....	17
2.2.1 Vertical stiffness	20
2.2.1.1 Vertical stiffness in Girls	21
2.2.2 Leg stiffness.....	22
2.2.2.1 Leg stiffness in girls	23
2.2.3 Joint stiffness.....	24
2.2.3.1 Joint stiffness in girls	25
2.3 Stiffness changes with growth and maturation	26
2.3.1 Time course of adaptation of global stiffness	26
2.3.2 Time course of adaptation of intrinsic stiffness	31
2.3.3 Determinants of stiffness increase throughout childhood and adolescence	32
2.3.3.1 Tendon material properties	33

2.3.3.2 Dimensional and mechanical properties of the tendon	34
2.3.4 Neurological modulation and influence of stiffness	35
2.3.4.1 Motor-unit activation and muscle preactivation	36
2.3.4.2 Antagonist co-contraction.....	37
2.3.4.3 Reflex contribution.....	38
2.4 Stiffness and training.....	40
2.4.1 Strength training	40
2.4.2 Plyometric training.....	41
2.4.4 Combined training.....	44
2.4.5 Sprint training	45
2.5 Conclusion.....	49
Chapter 3. Reliability of leg stiffness during vertical sub-maximal hopping in young female athletes	50
3.0 Prelude	50
3.1 Introduction	50
3.2 Methods.....	53
3.2.1 Participants	53
3.2.2 Study procedures	53
3.2.3 Testing protocols	54
3.2.3.1 Anthropometric and maturity measures	54
3.2.3.2 Hopping procedures.....	54
3.2.3.3 Data analyses	54
3.3 Statistical analyses	56
3.4 Results.....	57
3.5 Discussion.....	59
3.5.1 Change in mean	59
3.5.2 Absolute consistency.....	60
3.5.3 Agreement between sessions.....	60
3.5.4 Reliability of calculation methods.....	61
3.6 Limitations.....	61
3.7 Conclusion and practical applications.....	62
Chapter 4. Reliability of horizontal jumping and hopping in youth female athletes of differing maturity status	63
4.0 Prelude	63
4.1 Introduction	63

4.2 Methods.....	65
4.2.1 Participants	65
4.2.2 Study procedures	65
4.2.3 Testing protocols	66
4.2.3.1 Anthropometric and maturity measures	66
4.2.3.2 General jump and hop protocols	66
4.2.3.3 Specific broad jump and triple broad jump testing protocols	67
4.2.2.4 Broad hop and triple broad hop testing protocols.....	67
4.3 Statistical analyses	67
4.4 Results	68
4.5 Discussion.....	72
4.6 Limitations.....	74
4.7 Conclusion and practical applications	75
Chapter 5. Vertical and leg stiffness during sprinting in youth female athletes at varying stages of maturity.....	76
5.0 Prelude	76
5.1 Introduction	76
5.2 Methods.....	79
5.2.1 Participants	79
5.2.2 Study procedures	82
5.2.3 Testing protocols	82
5.2.3.1 Anthropometric and maturity measures	82
5.2.3.2 20-meter sprint procedures	83
5.2.3.3 Data analyses	83
5.3 Statistical analyses	86
5.4 Results	87
5.4.1 Vertical and leg stiffness differences.....	87
5.4.2 Spatio-temporal variable differences.....	88
5.5 Discussion.....	92
5.5.1 Absolute and relative vertical stiffness	92
5.5.2 Absolute and relative leg stiffness	93
5.5.3 Speed and spatio-temporal variables	94
5.6 Limitations.....	96
5.7 Conclusion and practical recommendations	97

Chapter 6. Leg stiffness in girls of different maturity status and its contribution to sprinting performance	98
6.0 Prelude	98
6.1 Introduction	99
6.2 Methods.....	102
6.2.1 Participants	102
6.2.2 Study procedures	103
6.2.3 Testing protocols	103
6.2.3.1 Anthropometric and maturity measures	103
6.2.3.2 Sub-maximal hopping	106
6.2.3.3 20-meter sprint	106
6.2.4 Data analyses	107
6.2.4.1 Absolute and relative leg stiffness	107
6.2.4.2 Sprint time and maximal velocity.....	107
6.3 Statistical analyses	108
6.3.1 Difference in leg stiffness across maturation	108
6.3.2 Contribution of leg stiffness to sprint performance	109
6.4 Results	110
6.4.1 Differences in leg stiffness between maturity group	110
6.4.2 Contribution of leg stiffness and anthropometric variables to sprint performance.....	114
6.5 Discussion.....	117
6.5.1 Differences in absolute leg stiffness between maturity groups.....	117
6.5.2 Differences in relative leg stiffness between maturity groups.....	119
6.5.3 Contribution of leg stiffness and anthropometric variables to sprint performance.....	120
6.6 Limitations.....	122
6.7 Conclusion, practical recommendations.....	122
Chapter 7. The effects of linear sprint training compared to plyometric training on leg stiffness in youth female athletes	124
7.0 Prelude	124
7.1 Introduction	124
7.2 Methods.....	127
7.2.1 Participants	127
7.2.2 Study procedures	130
7.2.3 Testing protocols	130
7.2.3.1 Anthropometric and maturity measures	130

7.2.3.2 Sub-maximal hopping	131
7.2.3.3 Horizontal jumping and hopping.....	131
7.2.3.3.1 Broad jumps	132
7.2.3.3.2 Broad hops	132
7.2.4 Training programs	132
7.2.4.1 Plyometric training program	133
7.2.4.2 Sprint training program.....	135
7.2.5 Data analyses	137
7.3 Statistical analyses	137
7.3.1 Linear mixed-effects model- time, group, maturity status, group x time	137
7.4 Results.....	139
7.4.1 Fixed effects	139
7.4.1.1 Fixed effect of time	139
7.4.2.2 Fixed effect of group	144
7.4.2.3 Fixed effect of maturity status	144
7.4.3 Interaction effects- group x time.....	146
7.5 Discussion.....	149
7.5.1 Effect of training on leg stiffness.....	149
7.5.2 Effect of maturity status on leg stiffness.....	151
7.5.3 Horizontal hopping and jumping.....	153
7.6 Limitations.....	154
7.7 Conclusion and practical recommendations.....	155
Chapter 8. The effect of plyometric training and moderating variables on stretch-shortening cycle function and physical qualities in female post peak height velocity volleyball players	157
8.0 Prelude	157
8.1 Introduction	158
8.2 Methods.....	160
8.2.1 Participants	160
8.2.2 Study procedures	161
8.2.3 Testing protocols	162
8.2.3.1 Anthropometric and maturity measures	162
8.2.3.2 Sub-maximal hopping	162
8.2.3.3 Horizontal jump and hop tests.....	163
8.2.3.4 Drop jump	164
8.2.3.5 Generalized joint hypermobility.....	164

8.2.4 Training program	165
8.3 Statistical analyses	167
8.4 Results	168
8.4.1 Data normality	168
8.4.2 Training effect.....	170
8.4.3 Effect of moderators	172
8.5 Discussion.....	177
8.5.1 Training effect.....	177
8.5.2 Effect of moderators	181
8.5.2.1 Effect of training volume	183
8.5.2.2 Effect of body mass	184
8.5.2.3 Effect of age and maturity.....	185
8.5.2.4 Effect of hypermobility.....	186
8.6 Limitations.....	187
8.7 Conclusion.....	187
8.8 Practical recommendations	188
Chapter 9. General Discussion	189
9.1 Summary and conclusion	189
9.2 Main findings.....	193
9.3 Practical applications.....	195
9.4 Limitations.....	196
9.5 Future research directions	198
References.....	200
Appendix A. AUT ethics approval.....	227
Appendix B. Czech ethics approval	228
Appendix C. Covid ethics- Home institution	229
Appendix D. Reliability and cross-sectional consent form.....	231
Appendix E. Intervention consent form	232
Appendix F. Reliability and cross-sectional assent form- Ages 7-11	233
Appendix G. Reliability and cross-sectional assent form- Ages 12-15	235
Appendix H: Intervention assent form- Ages 7-11.....	236
Appendix I. Intervention assent form- Ages 12-15	238

ABSTRACT

Explosive rebounding movements such as hopping and sprinting that rely on the stretch-shortening cycle (SSC) and elastic properties such as stiffness, are essential for sports performance. While fast-SSC tasks like sub-maximal hopping and sprinting have been assessed for reliability, maturity-related differences and training-related differences in boys, similar investigations remain unexplored in girls. This thesis sought to understand the natural development of rebounding ability of young girls, assessed by leg stiffness, and how leg stiffness develops through training. The introduction and literature review provide an overview of stiffness behavior, how it is regulated, how global measures of stiffness change with maturation and training during sub-maximal hopping and sprinting. These topics established the thesis framework and justification for further investigation in stiffness behavior.

Chapter 3 examined the measurement error of leg stiffness during the most suitable assessment task, sub-maximal hopping, across multiple hopping frequencies and calculation methods in young girls. This chapter revealed an acceptable average coefficient of variation percentage (CV%) range of 3.89% to 9.44%, and excellent intraclass correlation coefficient (ICC) ($ICC > 0.9$) values across all hopping frequencies and calculation methods. These findings also revealed that hopping at 2.5 Hz on the dominant leg and using the ‘all contacts’ calculation method were the most reliable leg stiffness conditions. The reliability of additional explosive tasks across maturity stages were examined in Chapter 4. It was shown that horizontal jumping tasks were more reliable than horizontal hopping tasks, with coefficients of variation (CVs) of 2.82%-3.13% for jumping and 3.15%-7.46% for hopping. Single hops proved more reliable than triple hops, with CVs of 3.21%-4.5% compared to 3.15%-7.46%. All average intraclass correlation coefficients (ICCs) were above 0.9, indicating high reliability for both tasks when an additional familiarization session is included.

Chapters 5 and 6 examined maturity-related differences during sprinting and unilateral sub-maximal hopping respectively. Chapter 5 found significant differences ($g = 1.51-1.64$) for

vertical stiffness (K_{vert}), relative vertical stiffness ($\text{Rel}K_{\text{vert}}$), leg stiffness (K_{leg}), and relative leg stiffness ($\text{Rel}K_{\text{leg}}$) between the PRE and MPUB stages. Significant differences ($g = 1.66-1.79$) for also discovered for speed and step length (SL) between the PRE and MPUB stages. However, due to high CV values for K_{leg} and $\text{Rel}K_{\text{leg}}$ (11-16%) and systematic changes in SL during reliability tests, these results should be interpreted cautiously. Overall, stiffness and SL changes between PRE and MPUB stages may enhance sprint performance in young girls. Chapter 6 examined leg stiffness differences of a combined pre-pubertal (PRE) and early pubertal group of girls (EPUBPRE), compared to mid-pubertal girls (MPUB), and late pubertal girls (LPUB). The findings demonstrated large and significant differences in absolute leg stiffness between EPUBPRE and MPUB ($g = 1.27$, 95% CI = 0.81, 1.73) and between MPUB and LPUB ($g = 1.27$, 95% CI = 0.85, 1.69) for unilateral sub-maximal hopping at 2.5 Hz on the dominant leg. Significant differences were also found between EPUBPRE and MPUB for relative leg stiffness ($g = 0.48$, 95% CI = 0.16, 0.80). Thus, maturity status appears to impact both absolute and relative leg stiffness development substantially in young girls.

In Chapter 7, plyometric and sprint training were used to target stiffness enhancement, with plyometric training inducing stiffness adaptations at 2.5 Hz on the dominant leg. Furthermore, this adaptation (4.4%) exceeded the within subject error of 3.89% established in Chapter 3. Chapter 8 demonstrated a similar effect of plyometric training on leg stiffness during sub-maximal at 2.5 Hz on the dominant leg. The results of these intervention studies demonstrate that plyometric training is beneficial for improving leg stiffness in young girls. Finally, Chapter 9 outlined a summary of the findings, practical applications, limitations and future research directions of stiffness in young girls.

LIST OF FIGURES

Figure 1.1. Thesis structure	13
Figure 2.1. The spring-mass model during vertical sub-maximal hopping	19
Figure 2.2. Maturity-related changes in stiffness.....	30
Figure 5.1. Maturity group differences for vertical and leg stiffness.....	90
Figure 6.1. Maturity group differences in leg stiffness	113
Figure 6.2-6.6. 20m sprint time partial correlations.....	116
Figure 7.1. Within-group differences in absolute leg stiffness	140
Figure 7.2. Within-group differences in relative leg stiffness.....	141
Figure 7.3. Leg stiffness coefficients per maturity status.	145
Figure 8.1. Correlation analysis between changes in dependent variables and body mass, total generalized joint hypermobility (GJH) score, and training volume.....	176

LIST OF TABLES

Table 2.1. Stiffness intervention studies quantified by hopping	47
Table 2.2. Stiffness intervention studies quantified by drop jumping.....	48
Table 3.1. Absolute leg stiffness reliability	58
Table 4.1. Horizontal jump and hop reliability results for the less mature group	70
Table 4.2. Horizontal jump and hop reliability results for the more mature group	71
Table 5.1. Participant characteristics per maturity group	81
Table 5.2. Group differences in stiffness and sprint spatio-temporal variables using Hedges' <i>g</i> effect size and 95% CI	89
Table 5.3. Average CV% + 95% confidence intervals for stiffness and spatio-temporal variables	91
Table 6.1. Participant characteristics per maturity group	105
Table 6.2. Maturity group differences in leg stiffness	112
Table 6.3. Unstandardized, standardized coefficients with 95% confidence intervals, <i>t</i> -values, <i>p</i> -values, part, and partial correlations	115
Table 7.1. Anthropometric characteristics per training group	129
Table 7.2. Plyometric training program.....	134
Table 7.3. Sprint training program	136
Table 7.4. Absolute and relative leg stiffness relative to the control group	142
Table 7.5. Absolute and relative jump and hop distance relative to the control group	143
Table 7.6. LMM beta coefficients, SE, <i>p</i> -value for group x time interactions for leg stiffness	147
Table 7.7. LMM beta coefficients, SE, <i>p</i> -value for group x time interactions for horizontal jumps and hops.....	148
Table 8.1. Training program details.	166
Table 8.2. Characteristics of the participants.	169
Table 8.3. The effect of the plyometric training program on the dependent variables	171
Table 8.4. Values of regression coefficients	173
Table 8.5. Statistical significances of regression coefficients	174
Table 8.6. Eta-squared of regression coefficients	175

LIST OF COMMON ABBREVIATIONS

%: Percentage

ΔL : Change in leg length

$\Delta\theta$: Change in joint angle

Δy : Center of mass displacement

10Hop: 10 appropriate hops

AC: All contacts

AC5: All contacts within 5% of average contact time

ANOVA: Analysis of variance

ART: Athletic ready position

BF%: Body fat percentage

BJ: Broad jump

BM: Body mass

Bpm: Beats per minute

BW: Body weight

CG: Control group

CI: Confidence interval

cm: Centimeters

CMJ: Countermovement jump

CSA: Cross-sectional area

CV: Coefficient of variation

D/f: Raw difference

d: Cohen's *d* effect size

D: dominant leg

e.g.: Example EPUBPRE: Combined EPUB (Early pubertal girls) and PRE (prepubertal girls)

ES: Effect size

EXP: experimental group

FIFA: Fédération internationale de football association

Fmax: Maximal force

g: Acceleration due to gravity

g: Hedge's g effect size

gr: Significant effect of group

GJH: Generalized joint hypermobility

gNMT: Neuromuscular training combined with gymnastics training group

gt: Significant group x time interaction

GYM: Gymnastics training group

Hz: Hertz

i.e.: That is

ICC: Intraclass correlation coefficient

K: Stiffness

Kankle: Ankle stiffness

kg: Kilograms

Khip: Hip stiffness

Kjoint: Joint stiffness

Kknee: Knee stiffness

Kleg: Absolute leg stiffness

kN/m: Kilonewtons per meter

Kvert: Absolute vertical stiffness

Lt: Left leg

L: Standing leg length

LL: Leg length

LMM: Linear mixed effects model

LPUB: Late pubertal girls

M: Joint moment

M: Mass

m: Meter

m: Significant effect of maturation

Matstatus: Maturity status

MDAH: Multi-directional ankle jumps

MDJLC: Multi-directional jump landing combination

Mod: Moderate

MPUB: Mid pubertal girls

ms: Milliseconds

MTU: Muscle-tendon unit

N/A: Not applicable

N/R: Not reported

ND: Non-dominant leg

n: Number of participants

NMT: Neuromuscular training

PAH: Predicted adult height

PHV: Peak height velocity

PT: Plyometric training

PTG: Plyometric training group

Q-Q plots: Quantile-quantile plots

r : Pearson's correlation coefficient

Rt: right leg

R^2 : Coefficient of determination

RelBJ: Relative broad jump

RelKleg: Relative leg stiffness

RelKvert: Relative vertical stiffness

RelSBHL: Relative single broad hop left

RelSBHR: Relative single broad hop right

RelTBHL: Relative triple broad hop left

RelTBHR: Relative triple broad hop right

RelTBJ: Relative triple broad jump

RMANOVA: Repeated measures analysis of variance

RSI: Reactive strength index

Rt: Right leg

s: Seconds

SBHL: Single broad hop left

SBHR: Single broad hop right

SD: Standard deviation

SE: Standard error

SSC: Stretch-shortening cycle

SSeffect: Sum of squares associated with the moderator

SStotal: Total sum of squares

ST: Sprint training

STG: Sprint training group

STRT: Strength training

TBHL: Triple broad hop left

TBHR: Triple broad hop right

TBJ: Triple broad jump

T_c : Contact time

T_f : Flight time

vs: Versus

β : Beta coefficients

η^2 : Eta squared statistic

π : Half period of the sine wave

ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly noted in the acknowledgements), nor used artificial intelligence tools or generative artificial intelligence tools (unless it is clearly stated, and referenced, along with the purpose of use), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning.



Chapter 8 of this thesis represents a published article, while Chapter 3 and 6 have been submitted to peer-reviewed journals for consideration for publication. The contributions of myself and the various co-authors of these papers are outlined on the *Publications* page below. All co-authors have approved the inclusion of the joint work in this doctoral thesis.

Richard Courtney Sylvester

CO-AUTHORED WORKS

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CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Explosive movements like hopping, jumping and sprinting are key components for successful performance and participation in sports (Lloyd et al., 2015c). These movements involve the stretch-shortening cycle (SSC), which relies on the elastic characteristics of the musculoskeletal system, including stiffness (Kums et al., 2005, Carrasco-López et al., 2019, Radnor et al., 2017, De Ste Croix et al., 2021). Stiffness promotes the resistance to deformation under applied forces, and can be modelled across the whole body, the leg, individual joints, muscles and tendons (Butler et al., 2003, Brughelli and Cronin, 2008a). For example, vertical stiffness characterizes the force to deformation ratio of the center of mass, whereas leg stiffness describes the ratio of force to leg compression (Farley and Morgenroth, 1999). Adequate vertical and leg stiffness during SSC tasks like vertical hopping and sprinting limit excessive displacement of the center of mass, compression of the leg and encourage the execution of spring-like force application. This, in turn, enhances the ability to bounce off the ground, optimizes elastic energy storage and reutilization, enhances braking and propulsive forces, and reduces ground contact time (Clark and Weyand, 2014, Latash and Zatsiorsky, 1993).

When SSC tasks are executed quickly (< 250 ms), they are classified as “fast-SSC” activities (Lloyd et al., 2011b). Although stiffness can be quantified using maximal or sub-maximal rebounding tasks, sub-maximal hopping may be the most suitable method for youth, particularly when utilizing field-based devices such as mobile contact mats (Lloyd et al., 2009, Maloney and Fletcher, 2018). Sub-maximal hopping allows young individuals to rebound off the ground in an energy efficient manner, whereas maximal tasks make this more challenging (Lloyd et al., 2009). Energy-efficient hopping stresses fast-SSC function and minimizes deformation for a given force applied. This has been found to optimize the force-to-deformation ratio when performed at an individual's natural bouncing frequency, which for youth is around 2.5 Hz (Lloyd et al., 2009, Beerse and Wu, 2016). Leg stiffness measured during bilateral sub-maximal hopping at 2.5 Hz has shown to be reliable in girls (De Ste Croix et al., 2017). However, there is limited data on the reliability of unilateral sub-maximal

hopping at various frequencies and different calculation methods in girls. Considering the role of stiffness in mediating the SSC and the importance of jumping and hopping in sports, it is essential to establish reliable testing methods for girls to accurately measure these key qualities.

Vertical and leg stiffness, as measured during various fast-SSC tasks such as sub-maximal hopping, maximal hopping, and sprinting, have been shown to improve with age and maturation in boys. Notable differences are observed across different age and maturity groups (Lloyd et al., 2011b, Laffaye et al., 2016, Meyers et al., 2015a, Meyers et al., 2016, Lehnert et al., 2020). During childhood, boys display linear increases in both absolute and relative stiffness (Lloyd et al., 2011b). However, during adolescence, growth-related changes in body mass and other anthropometric factors can influence the development of absolute stiffness (Lloyd et al., 2011a). To account for the influence of anthropometric factors and gain insight into changes unrelated to body size (e.g., muscle preactivation), researchers have evaluated relative stiffness variables. These variables include stiffness relative to body mass (Waxman et al., 2018) and stiffness relative to both body mass and leg length (Lloyd et al., 2009, De Ste Croix et al., 2017). Relative stiffness measures may provide insight into factors beyond body size that influence the ability to rebound off the ground (Lloyd et al., 2011b).

Leg stiffness development across childhood and adolescence during fast-SSC tasks such as sub-maximal hopping and sprinting in girls has been documented in a few studies to date. Moeskops et al. (2020) examined differences in relative vertical stiffness and discovered that pubertal girls had significantly higher values during drop jumping compared to early pre-pubertal girls. The higher relative vertical stiffness in pubertal girls likely contributed to their increased jump height. Elsewhere, adolescent girls have shown improvements in absolute leg stiffness between ages 11 and 16, followed by a decline between ages 17 and 18 during maximal hopping (Laffaye et al., 2016). Meanwhile, relative leg stiffness ($\text{kNm/kg}^{-0.66}$) in girls appears to plateau during maximal hopping between ages 11-19 (Laffaye et al., 2016). Absolute and relative leg stiffness changes appear to be influenced by the measurement task, athletic background, maturation estimation method, and study design (Laffaye et al., 2016, Lehnert et al., 2020, De Ste Croix et al., 2021, Lloyd et al., 2011b). For example, the plateau

of relative leg stiffness with age in girls during maximal hopping, differs to the changes that occur with age during sub-maximal hopping (Laffaye et al., 2016, Lehnert et al., 2020). During sub-maximal hopping, a large significant decline ($g = -0.97$) in relative leg stiffness has been noted between ages 15-16 (Lehnert et al., 2020). Collectively, the existing literature appears to be equivocal, and research is warranted to better understand maturity-related differences in absolute and relative leg stiffness across different hopping frequencies in young girls.

During sprinting, leg stiffness has been examined as a distinct quality from vertical stiffness, where leg stiffness comprises a vertical and horizontal component (Farley and Gonzalez, 1996). The role of stiffness in sprinting, has been shown to facilitate efficient force application during the ground contact phase, thereby affecting sprint variables such as step frequency, step length, and ground contact time (Meyers et al., 2019, Meyers et al., 2016, McMahon and Cheng, 1990, Moir et al., 2018, Cavagna et al., 1977, Clark and Weyand, 2014). Researchers have reported age and maturity-related differences in absolute vertical and leg stiffness during non-motorized sprinting and overground sprinting in boys (Rumpf et al., 2013, Meyers et al., 2019, Meyers et al., 2016). However, there are no studies where researchers have assessed the maturity-related differences in vertical or leg stiffness during sprinting in girls. Thus, there is a need to investigate the maturity-related differences in vertical and leg stiffness during sprinting in girls.

Researchers have explored ways to enhance stiffness in girls beyond its natural development (Moeskops et al., 2022a), using mostly combined training methods (Moeskops et al., 2022a, Moeskops et al., 2018a, De Ste Croix et al., 2018). Combined training methods have resulted in trivial to large improvements in absolute stiffness ($g = 0.12-1.04$) in pre-adolescent and adolescent girls. Among adolescent girls, particularly those in mid- and post-peak height velocity (PHV) stages, a moderate effect was observed ($d = 0.6$) (Moeskops et al., 2018a, De Ste Croix et al., 2018). Conversely, relative forms of stiffness have shown moderate to large changes ($g = -0.97-0.56$) among preadolescent and adolescent girls (Moeskops et al., 2022a, De Ste Croix et al., 2018). However, the effects of combined training in girls remain unclear, potentially due to uncertainty about which specific training methods and underlying

mechanisms most effectively elicit stiffness adaptations in girls (Moeskops et al., 2022a, Moeskops et al., 2018a). Exploring the isolated effects of individual methods such as plyometric and sprint training on stiffness may elucidate the mechanisms that elicit stiffness adaptations in girls.

Mechanisms of stiffness enhancement include those that target the control mechanisms of SSC function such as, neuromuscular recruitment and activation prior to and in the early phases of ground contact, increased stretch-reflex contribution and optimization of elastic energy storage and return (Oliver and Smith, 2010, Radnor et al., 2017, Millett et al., 2018). Plyometric and sprint training specifically target these SSC mechanisms (Ramirez-Campillo et al., 2023a, Moran et al., 2017b), and both types of training involve high rates of force development, power, and impulse that aid in propelling the body upward and forward (Clark and Weyand, 2014, Moir et al., 2018, Oliver et al., 2013, Ramirez-Campillo et al., 2023a). These methods also emphasize reactive force application against the ground, which requires muscle preactivation and stretch-reflex contribution to promote a “stiff” landing strategy to control and coordinate the SSC (Oliver and Smith, 2010). However, several determinants of rebounding ability (e.g., leg stiffness, center of mass displacement, peak vertical ground reaction force, and contact time), have been shown to influence plyometric performance more than sprinting (Millett et al., 2018). Furthermore, center of mass displacement and contact time during vertical drop jumping and horizontal drop jumping, are better than those observed in running (Millett et al., 2018, Moeskops et al., 2020, Moeskops et al., 2022a). To date, there is no consensus as to the most appropriate training method to enhance leg stiffness in young girls. Plyometric and sprint training focus on crucial stiffness enhancement mechanisms, offer fewer resource limitations, and have received comparatively less investigation in girls (Ramirez-Campillo et al., 2023a). Yet, to date research has not compared the efficacy of these training modes on measures of stiffness in young females (Moran et al., 2023, Gevat et al., 2012).

The effectiveness of a training program is dependent on the external and internal moderator variables (Ramirez-Campillo et al., 2023a). Internal moderator variables include variables such as age, maturity, and body size (Radnor et al., 2017, Simmons, 2000), while external

moderator variables include programming variables like training volume and intensity (Johnson et al., 2011, Asadi et al., 2017b, Moran et al., 2018b). Characteristics like age and body size have been assessed for their effect on countermovement jump (CMJ) height in girls (Moran et al., 2018b, Ramirez-Campillo et al., 2023a). Findings suggest that younger, shorter, and lighter girls show a better response to plyometric training aimed at improving CMJ height (Moran et al., 2018a). However, there is limited research on how internal (e.g., maturity, body mass) and external (e.g., training volume) factors influence the impact of plyometric training on sub-maximal hopping and various horizontal jumping and hopping tasks in girls (Moran et al., 2023, Ramirez-Campillo et al., 2023b, Moran et al., 2018a). Moreover, the effect of plyometric training on stiffness in healthy individuals of all ages has been reported to have small but significant effect sizes. However, the impact of plyometric training on stiffness in girls remains largely unexplored. Therefore, further examination of this effect in girls is warranted.

1.2 THESIS RATIONALE

Performance in fast-SSC tasks like sprinting and vertical hopping rely on the ability to rebound off the ground effectively. This ability is mediated by stiffness, which minimizes excessive deformation of musculoskeletal components like muscles and tendons. The ability to limit excessive deformation enhances the storage and reutilization of elastic energy, encourages stretch reflex contributions, heightens muscle activity and quickens the transfer of force to bone. Ultimately, these factors will help increase the rate of force development, reduce ground contact time, increase braking and propulsive forces and improve impulse to aid performance in time dependent tasks in sport (Clark and Weyand, 2014, Latash and Zatsiorsky, 1993). Furthermore, stiffness can adjust to offset growth and maturity-related increases in body mass and leg length or changes in athletic task intensity that require large forces in a small amount of time (Lloyd et al., 2012a). For example, increasing running speed, a common task among active children and youth, would require higher stiffness to accommodate the body crashing to the ground faster with every step. However, the natural development of stiffness throughout childhood and adolescence, has been better documented in boys compared to girls during various fast-SSC tasks (Lloyd et al., 2011b). The reliability of stiffness measurements is largely unknown during sub-maximal hopping at different

frequencies and calculation methods. Additionally, how stiffness differs between girls of varying maturity during sub-maximal hopping and sprinting, and how training affects stiffness in girls during accessible training methods like plyometrics and sprinting is also largely unknown. Given the influence of growth and maturation on physical qualities in girls, the limited data on stiffness behavior during childhood and adolescence, and the scarcity of research on training-related stiffness improvements, this thesis aims to address several gaps in the literature. These include measurement error, maturity-related differences, and training-induced improvements in stiffness in young girls.

1.3 AIMS/OBJECTIVES

Considering the existing evidence on stiffness in young girls, the aim of this thesis is to investigate the rebounding ability of girls by examining maturity-related and training-induced differences in global stiffness during sub-maximal hopping and sprinting. To address this aim, the thesis consisted of a literature review and six experimental chapters. The experimental chapters included two reliability chapters, two cross-sectional chapters and two intervention chapters. The specific aims of the thesis were to:

1. Review the literature related to the global stiffness behavior of the musculoskeletal system, and how it develops according to maturity and training.
2. Assess the inter-day reliability of absolute and relative leg stiffness in girls during vertical sub-maximal hopping at various frequencies.
3. Assess the inter-day reliability of horizontal jumping and hopping in girls of differing maturity status.
4. Examine the intra-day reliability of absolute and relative leg stiffness during a 20-meter sprint in girls of different maturity levels.
5. Investigate the maturity-related differences in absolute and relative vertical and leg stiffness and sprint spatio-temporal variables during a 20-meter sprint in girls.
6. Examine how absolute and relative leg stiffness differ among girls of varying maturity status during unilateral vertical sub-maximal hopping and their impact on sprint performance in young girls.

7. Examine the effect of horizontal plyometric training compared to linear sprint training on absolute and relative leg stiffness, and absolute and relative horizontal jumping and hopping ability in young girls.
8. Explore how horizontal plyometric training and key participant and training moderators influence leg stiffness and the horizontal jump and hop distance in post-PHV girls.

1.4 PROJECT CONTEXT

This doctoral research was initially supported by, and based in, a private fitness and coaching facility named the Athlete Factory New Zealand (NZ), in Mount Maunganui, NZ. The researcher entered into an agreement with the Athlete Factory NZ, where 20 hours of responsibilities would be completed per week in exchange for a scholarship. Responsibilities included coaching a range of youth and young adult strength and conditioning programs. Shortly after the researcher's confirmation of candidature, the sudden outbreak of the Covid-19 pandemic and the subsequent lockdown restrictions, caused all in-person plans for data collection to be postponed until further notice. The Athlete Factory NZ relied heavily on international business; thus, the lockdown forced the Athlete Factory NZ to make staff redundancies. This resulted in the loss of scholarship, which compelled the researcher to return home to Canada prior to the Canadian and New Zealand borders closing.

Upon arrival in Canada, there was a closure of the Canadian and New Zealand borders, and a suspension of all non-essential in-person activities such as sport. There were no in-person data collection-related activities permitted, so a decision was taken to undertake a one-year leave of absence. Afterwards, the relevant research equipment was purchased to allow data collection to be conducted in Canada. Overall, the Covid-19 pandemic imposed several negative effects. *Firstly*, numerous facilities such as schools refused to rent to outside parties, imposing significant constraints on the city's sports system. This led all sports teams, community groups, and physical activity organizations to rent from a limited number of suitable indoor facilities. *Secondly*, universities, and non-purpose-built facilities like ice hockey rink concourses, building hallways, were unable to accommodate fitness testing for the purposes of this project. This inability to accommodate testing was due to restrictions on

the number of people present in the facility as well as in certain parts of the building. *Thirdly*, repeated lockdowns affected data collection procedures and caused fear in prospective participants' families. For example, on two occasions, lockdowns caused the cessation of reliability study data collection on the last day of testing, which limited the sample sizes for both reliability studies. Recruitment was also exceedingly difficult due to fear of parents having their children involved in activities that involved extra or unfamiliar cohorts of children. Many parents preferred their children to remain with the activities they were participating in prior to the pandemic and did not want to engage in any new or unfamiliar activities. *Fourthly*, there was also a concurrent movement within the Canadian sport system and beyond called the Safe Sport movement, which stemmed from the uncovering of systemic abuse within sports. This 'reckoning' came with wide-sweeping policy change in sport and a healthy fear from parents in allowing young girls to work with adult males. This fear was communicated directly by several sport organizations and parents to the researcher. Overall, these factors made recruiting participants extremely difficult and forced the researcher to seek opportunities in other cities across Canada and in Europe. Specifically, throughout the course of the doctorate, data collection was conducted in four cities across Canada and one city in Europe at financial cost to the researcher.

1.5 ORIGINALITY, SIGNIFICANCE, RIGOR

1.5.1 Originality

Originality in a research project refers to how much it offers new insights or makes distinctive contributions to the existing body of knowledge. This thesis is novel and original due to its focus on stiffness for an underrepresented population in the literature. It assesses leg stiffness during sub-maximal hopping and sprinting, considers maturity status, and explores the use of sprinting as a training method to enhance leg stiffness. The specific elements of this thesis that are original are outlined below:

1. In girls, prior studies have mainly focused on measuring leg stiffness during bilateral sub-maximal hopping at 2.5 Hz (Moeskops et al., 2018a) or unilateral sub-maximal hopping at 2.2 Hz (Waxman et al., 2018). However, these studies have not compared different leg stiffness calculation methods or assessed leg stiffness under various hopping conditions (i.e.,

frequencies) using simpler and more cost-effective field-based devices like mobile contact mats. The chosen calculation method can significantly impact the reliability of rebounding tests (Moresi et al., 2015). Furthermore, assessing leg stiffness at different frequencies allows for a wider description of leg stiffness behavior and provides insight into how the musculoskeletal system adjusts under variable conditions in girls.

2. This thesis was the first to explore the difference in absolute and relative leg stiffness between maturity stages during unilateral sub-maximal hopping at 2.5 Hz. Hopping at 2.5 Hz is the most suitable frequency due to a high ratio of force to deformation (Lloyd et al., 2009, Beerse and Wu, 2016). It was discovered that absolute leg stiffness differed significantly between all stages of maturity, while relative leg stiffness differed only between the least mature and most mature stages.

3. Vertical and leg stiffness have been shown to contribute to sprint performance across maturation in boys (Meyers et al., 2016). However, similar maturity-related investigations in girls remain unexplored. This thesis addresses this gap by examining the maturity-related differences in both absolute and relative vertical and leg stiffness during sprinting in girls, a previously unstudied area. The findings of this investigation revealed significant post-hoc differences between PRE and MPUB for all stiffness variables.

4. The discovery of maturity-related differences of stiffness during sprinting encouraged further exploration of the contribution of stiffness and key anthropometric variables during sprinting. Specifically, it was revealed that absolute and relative leg stiffness during unilateral sub-maximal at 2.5 Hz, along with anthropometric variables (i.e., body mass, body fat%, leg length) explained 48.4% of sprint performance in girls. These variables have not previously been explored for their contribution to sprinting in girls.

5. All chapters in this thesis have analyzed data according to biological maturity. Estimating biological maturity using the predicted adult method has occurred in limited capacity throughout the literature (Lloyd et al., 2014b, Khamis and Roche, 1994, Moeskops et al., 2020, Cumming et al., 2017). Assessment of maturity status helps account for the variability that exists for a given participant that age does not account for (Lloyd et al., 2014b).

6. This thesis is the first to compare the effects of plyometric and sprint training on leg stiffness development in girls. Prior research has primarily focused on combined training

methods, which may not identify the isolated effects of a given training method on stiffness. Plyometric and sprint training involve stiffness-mediated SSC actions (Moran et al., 2023). Additionally, plyometric and sprint training are accessible methods with fewer resource constraints for children and youth. The findings of this study demonstrated a significant enhancement in leg stiffness due to plyometric training, compared to a control group during sub-maximal hopping at 2.5 Hz on the dominant leg.

7. There are no studies available which assess the effect of plyometric training on leg stiffness in post-PHV girls. Only one other study exists in pre-pubertal girls which has investigated the effect of plyometric training only on stiffness in girls (Katsikari et al., 2020). The findings of the current study revealed the effectiveness of horizontal plyometric training in improving leg stiffness during sub-maximal hopping at 2.5 Hz on the dominant leg.

1.5.2 Significance

Significance refers to the degree to which research has influenced, or is expected to influence, an academic field or practical application. One intervention study (Chapter 8) from this thesis has been published. It is the only solely plyometric intervention that has targeted leg stiffness measured during multiple sub-maximal hopping conditions in post-PHV girls. Other studies have mainly focused on combined training methods, with stiffness measured during drop jumping or one sub-maximal hopping condition (Moeskops et al., 2022a, De Ste Croix et al., 2018, Moeskops et al., 2018a). Chapter 3 provides comprehensive reliability data for absolute and relative leg stiffness during sub-maximal hopping that can be used as a source of reference for the typical noise expected in the test by young girls. For example, the within-subject error for sub-maximal hopping at 2.5 Hz on the dominant leg was 3.89%, indicating that training-related improvements must exceed this value to be deemed clinically significant. Chapter 3 is also the only investigation to compare different leg stiffness calculation methods during sub-maximal hopping. The discovery of the “all contacts” method as the most suitable calculation method allows researchers to maximize the number of hopping contacts used in a sample thus potentially increasing calculation accuracy while maintaining sample integrity. The findings from Chapter 5 described the natural development of vertical and leg stiffness during sprinting, while Chapter 6 described leg stiffness during unilateral sub-maximal hopping. Maturity-related descriptions of absolute and relative stiffness development provide

insight into the mechanisms that may underpin natural adaptations. For example, during childhood, neuromuscular-focused mechanisms may have influenced differences in leg stiffness, whereas in adolescence, these differences may be more influenced by morphological factors and body size. Chapter 7 and 8 provide evidence for the effectiveness of horizontal plyometric training on leg stiffness adaptations in young girls. It is recommended to include plyometric training from childhood through adolescence, emphasizing reactive exercises with brief ground contact for optimal stiffness development. These findings could influence youth strength and conditioning by advocating for customized, developmentally appropriate programs that target stiffness and the SSC for young girls.

1.5.3 Rigor

Rigour encompasses the clarity in articulating the research's purpose, the suitability of the research design, the complexity of chosen methodologies, and the robustness of the evidence provided. The present thesis showcases a sequence of coherent, interconnected studies featuring logical research questions aimed at addressing the proposed objectives. Some notable strengths of the research designs include the assessment of maturity status involving estimating the percentage of predicted adult height using prediction equations from the somatic data collected. This method has shown to be more accurate when estimating maturity status, in particular, when predicting periods of rapid growth in stature (Parr et al., 2020). *Secondly*, comprehensive reliability analyses in Chapters 3 and 4 using three different indicators of reliability, change in mean, average coefficient of variation percentage and intraclass correlation coefficient were utilized. These assessments were carried out over three sessions rather than two, which enhances the precision of the estimate of reliability measures. *Thirdly*, various appropriate and relevant statistical analysis methods (e.g., correlations, linear regressions, analysis of variances, effect sizes) were used to interpret the findings of each study. For example, the use of a large cross-sectional data set in Chapter 6, facilitated comprehensive maturity-related comparisons among study participants. Using a large dataset allowed the analysis of a substantial number of individuals representing each maturity group. This approach ensured that the comparisons were robust and statistically significant, providing a nuanced understanding of how maturity status might influence absolute and

relative leg stiffness during sub-maximal hopping in girls. In Chapter 7, a linear mixed effects model was used to address various sources of variability and mitigate challenges from data collection disruptions caused by the Covid-19 pandemic. This flexible and robust model was specifically chosen to handle the intricacies of a repeated measures design across different groups, effectively accounting for individual participant variability, as well as accommodating uneven or missing data. By doing so, it bolstered the statistical power of the study despite the constraints of a small sample size, as discussed in Mota et al. (2023) and Hamner and Tan (2022). Finally, the inclusion of a second intervention chapter provided a more comprehensive examination of the factors influencing plyometric training. These factors include participant moderators like body mass and training moderators such as volume. The inclusion of a two-tailed difference analysis on the change scores, along with the reporting of regression coefficients, correlation coefficients and eta square statistics provided transparency and robustness in the regression analysis. This more thorough examination may yield valuable insight into the specific elements influencing stiffness characteristics in young female athletes. Such insights can facilitate the development of more tailored training programs that address the unique needs of young girls.

1.6 Thesis structure

This thesis contains eight chapters which address Aims 1-8 as outlined in Figure 1.1. The first section consists of a literature review describing stiffness behavior throughout the musculoskeletal system and an explanation of how stiffness develops naturally and due to training. The second section contains two reliability chapters, one on sub-maximal hopping using a mobile contact mat and the other on horizontal jumping and hopping using a standard tape measure device. Section three consists of two cross-sectional studies. The first examines maturity-related vertical and leg stiffness differences during sprinting, while the second examines maturity-related absolute and relative leg stiffness differences during sub-maximal hopping. The last section involves two intervention studies, one comparing horizontal plyometric training and linear sprint training relative to a control group, and the other examining the effects of plyometric training and their moderators on SSC function in girls.

Stiffness during sub-maximal hopping and sprinting in youth female athletes

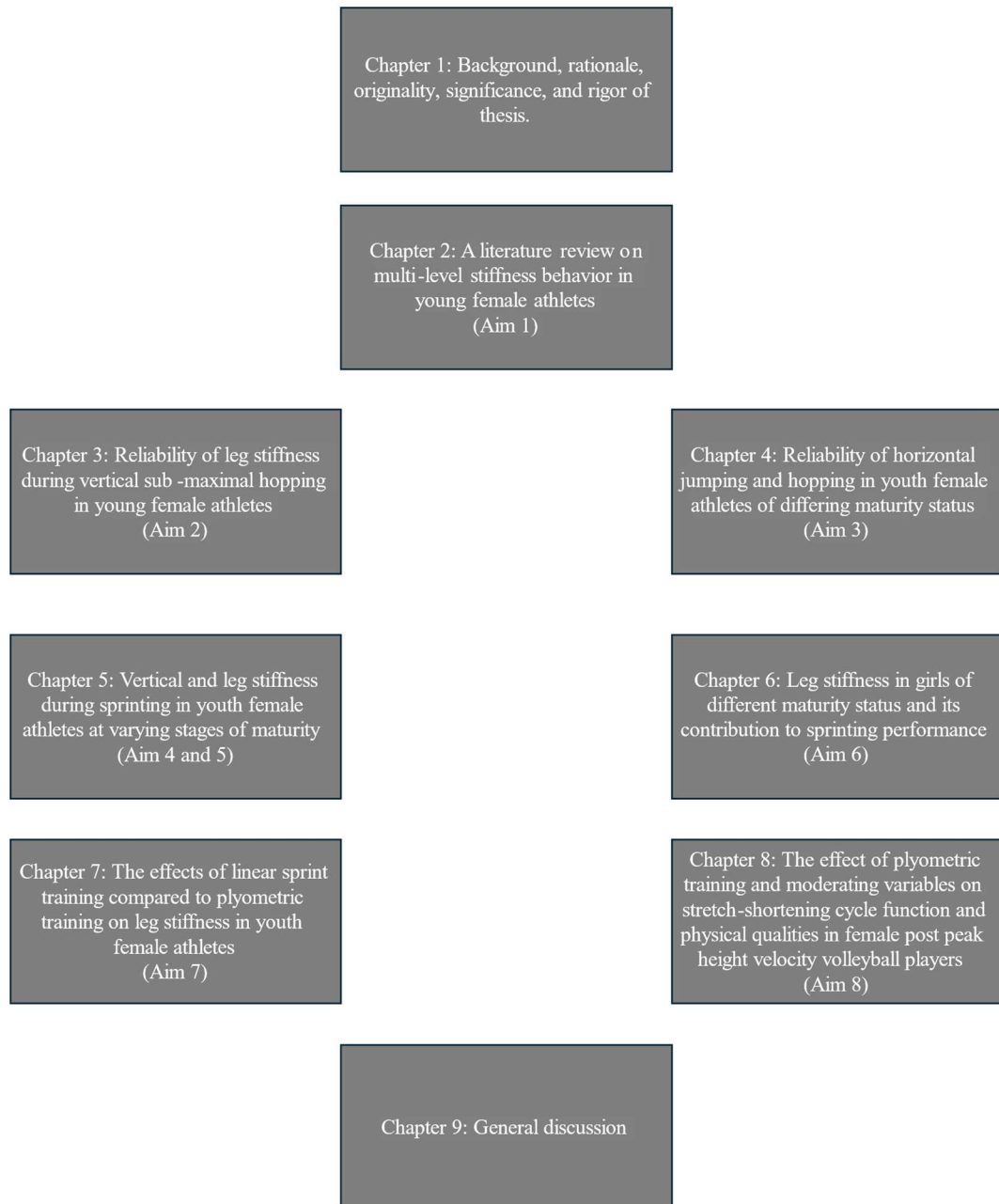


Figure 1.1. Thesis structure

CHAPTER 2. A LITERATURE REVIEW ON MULTI-LEVEL STIFFNESS BEHAVIOR IN YOUNG FEMALE ATHLETES

2.0 PRELUDE

It has been shown that stiffness has a role in mediating the stretch-shortening cycle (SSC) during rebounding tasks like sprinting and hopping. However, most research outlining the role of stiffness during these tasks has been conducted in boys and not girls. This Chapter aims to describe the literature informing the experimental studies in Chapters 3-8 that address the gaps related to stiffness behavior in girls. *Firstly*, the review provides an illustration of the relevant forms of global stiffness. *Secondly*, it examines how forms of global stiffness contribute to various sport-related tasks in girls. *Thirdly*, the review investigates how global and intrinsic stiffness develop across different maturity stages. *Fourthly*, the mechanisms that regulate stiffness in children compared to adolescents are investigated. *Finally*, stiffness training methods in girls are examined. Future research directions pertinent to the impact of stiffness on performance in girls according to maturation are presented throughout the review.

2.1 INTRODUCTION

Mechanical properties are physical characteristics that describe the response of a material to an applied load (Huda, 2022). Stiffness is the mechanical property of an object that describes the relationship between an applied force and the object's deformation magnitude (Brughelli and Cronin, 2008a, McMahon et al., 2012, Latash and Zatsiorsky, 1993). Stiffness is key in the interaction between the bones and soft tissues during fast-SSC movements like hopping (Butler et al., 2003, Brughelli and Cronin, 2008a). However, quantifying stiffness in its truest form is difficult due to the complexity of modelling each tissue's contribution, such as the intrinsic stiffness of the muscles, tendons, and articular tissues (Butler et al., 2003, Latash and Zatsiorsky, 1993). Alternatively, a simpler spring-mass model is applicable at the level of the entire body and the leg, while the torsional spring model pertains to the joint level and is frequently referred to as quasi-stiffness or global stiffness (Brughelli and Cronin, 2008a, McMahon et al., 2012, Serpell et al., 2012, Beerse and Wu, 2017). These more global forms

of stiffness, measured during fast-SSC tasks like hopping, are termed vertical, leg, and joint stiffness (Lambertz et al., 2003, Latash and Zatsiorsky, 1993).

Stiffness plays an important role in optimizing the SSC's ability to enhance force output during activities like sprinting, repetitive hopping, and jumping (Butler et al., 2003, Maloney et al., 2018, Pedley et al., 2020). During the eccentric phase of SSC movements, contractile elements (e.g., contractile proteins like myosin and actin) generate force while lengthening. Additionally, elastic elements, such as tendons, lengthen and store elastic energy, and receptors in the stretched muscle trigger the stretch-reflex. These processes heighten muscle activity in the propulsive phase by reutilizing stored elastic energy and taking advantage of the heightened stretch-reflex contribution (Brughelli and Cronin, 2008a, McMahon and Cheng, 1990, Butler et al., 2003, Sahrom et al., 2013, Turner and Jeffreys, 2010). During these fast-SSC tasks, higher amounts of stiffness allow large forces to be attenuated using a relatively smaller level of deformation of the center of mass, leg, joint, muscles, or tendons (Brughelli and Cronin, 2008a). This provision enables a swifter transmission of force from the muscle to the bone through the tendon, facilitating a quicker transition from eccentric to concentric muscular actions. It also enhances the reutilization of elastic energy, resulting in increased force output or faster movement speed (Radnor et al., 2017). However, stiffness behavior undergoes changes throughout childhood and adolescence because of growth and maturation processes (Radnor et al., 2017). This variation in stiffness behavior can impact performance in activities such as sprinting, hopping, and jumping throughout various stages of development. Understanding these changes is crucial for optimizing training and performance in athletes across different maturity stages.

Growth and maturation are profound processes within the human lifespan. Major musculoskeletal milestones include the fastest rate of growth in stature, termed peak height velocity (PHV), and the fastest rate of growth in body mass, termed peak weight velocity (Lloyd et al., 2014a, Lloyd et al., 2016a). These musculoskeletal milestones fall within a longer accelerated growth phase termed puberty. The pubertal phase also includes the growth and maturation of other bodily systems, including the nervous, cardiovascular, and reproductive systems (Naughton et al., 2000). However, the collective changes that occur

during puberty can enhance physical qualities such as the ability to generate force and movement speed (Lloyd et al., 2016a, Tumkur Anil Kumar et al., 2021). The bodily changes during puberty create a tumultuous period where growth and maturation processes significantly impact an individual's interaction with athletic tasks. These changes should be considered during skill development, physical training, and all forms of physical activity for children and youth.

Global and intrinsic stiffness behaviour throughout childhood and adolescence experiences a non-linear change due to growth and maturation. For example, absolute leg stiffness and musculotendinous stiffness in girls have been shown to increase non-linearly with age from adolescence to early adulthood during maximal hops, whereas relative leg stiffness plateaus during the same period (Laffaye et al., 2016). Furthermore, joint stiffness experiences maturation-dependent changes that vary according to the specific joint during drop jumps (Ford et al., 2010, Laffaye et al., 2016). There are also differences between boys and girls in how these levels of various types of stiffness change with growth and maturation (Lloyd et al., 2012a, Rumpf et al., 2013, Meyers et al., 2016). However, changes in the multi-level stiffness behaviour throughout childhood and adolescence depend on changes in the interaction between the muscle-tendon qualities and the neuromuscular qualities that regulate stiffness (Radnor et al., 2017, O'Brien et al., 2010a, Chalatzoglidis et al., 2021). Therefore, a thorough understanding of the natural development of stiffness depends on understanding of how stiffness regulatory qualities evolve.

There is a paucity of literature where researchers have quantified global or intrinsic forms of stiffness during sprinting in girls (Millett et al., 2018). There are also fewer stiffness studies where researchers investigated the effects of different training methods on global or intrinsic stiffness in girls of childhood age or between varying maturity statuses. Given these shortcomings, this review aims to understand how various forms of stiffness differ between stages of maturity in girls. The review, therefore, will aim to describe (i) key forms of global and intrinsic stiffness, (ii) how these forms of stiffness contribute to physical performance in girls, (iii) how global and intrinsic stiffness vary with maturation and/or between maturity stages, (iv) how the underlying stiffness mechanisms influence changes in stiffness

throughout childhood and adolescence in girls; (v) various stiffness training methods; and (vi) outline the future research directions relevant to the role of stiffness on performance in girls across maturation or between maturity stages.

2.2 THE STRUCTURE AND BEHAVIOUR OF GLOBAL AND INTRINSIC STIFFNESS

Global forms of stiffness can be modelled across the whole body, at the lower limb, and the joint. These forms of global stiffness are referred to as vertical, leg, and joint stiffness (Brughelli and Cronin, 2008a, Butler et al., 2003, Rabita et al., 2008). Stiffness can also be measured intrinsically in the tissues, as musculotendinous stiffness (Lambertz et al., 2003) and musculoarticular stiffness (Grosset et al., 2007, Grosset et al., 2005b). Musculotendinous stiffness describes the resistance to an applied load that occurs throughout the muscle-tendon complex (Lambertz et al., 2003, Ditroilo et al., 2011). This type of stiffness can be examined individually in the muscle (Latash and Zatsiorsky, 1993) or tendon directly through methods such as ultrasonography (Waugh et al., 2012), as well as motor driven ergometers using the so called quick-release technique (Lambertz et al., 2003). Conversely, musculoarticular stiffness describes the resistance to an applied load provided by the muscle-tendon unit (MTU) and articular structures such as ligaments and the joint capsule (Ditroilo et al., 2011). This type of stiffness can be measured by mechanical devices called actuators (e.g., servo-controlled motors), which expose joints to rhythmic oscillatory movements called sinusoidal length perturbations (e.g., imposed sinusoidal oscillations, free-oscillation technique) under active or passive conditions (Grosset et al., 2007, Ditroilo et al., 2011). With all this in mind, musculoarticular stiffness could be considered a ‘global’ form of stiffness given that it includes the articular structures. However, for the purposes of this thesis, it will be considered intrinsic given that it is measured in lab-based discrete settings, whereas vertical, leg and joint stiffness are measured during active field-based tasks (Ditroilo et al., 2011). Furthermore, a detailed description of intrinsic stiffness is beyond the scope of this article. Thus, this review will primarily conceptualize the various forms of global stiffness, in particular, leg stiffness. Where the term “stiffness” is used, it refers to the behavior of stiffness as a mechanical property and may refer to multiple forms of stiffness. Secondarily, this

review will describe how both global and intrinsic stiffness develop through growth and maturation-related changes and training-related changes.

Analyzing the stiffness of each specific bodily structure requires quantifying both deformation and force (Serpell et al., 2012, Butler et al., 2003). Assessing the degree of tissue deformation would necessitate measuring the strain level, which is defined as the change in length of a tissue under load relative to its resting length (Rodgers and Cavanagh, 1984, O'Brien et al., 2010a). However, because it is overly complex to model all the relevant tissues to quantify intrinsic stiffness, various SSC tasks are used to quantify global stiffness indirectly. The gold standard method for assessing global stiffness during SSC tasks involves the direct measurement of ground reaction forces using force plates and the direct visual quantification of deformation using motion capture (Brughelli and Cronin, 2008a). However, this technology is expensive and difficult to implement in the field. Instead, less expensive, more practical alternatives such as mobile contact mats can be used. To date, few studies have used contact mats to measure stiffness in girls compared to boys (De Ste Croix et al., 2017, Moeskops et al., 2018a, De Ste Croix et al., 2018, Moran et al., 2023).

Global stiffness measurement is accomplished by conceptualizing stiffness through simple biomechanical models. The first model is the spring-mass model and is described by a given mass supported by a spring (Figure 2.1). When a structure described by the spring-mass model rebounds off the ground, it oscillates down and up during the ground contact phase. During the downward portion, the spring is compressed and builds up force to resist deformation and stores elastic energy. It recoils during the upward portion and reutilizes elastic energy (Brughelli and Cronin, 2008a, McMahon et al., 2012). The torsional spring model describes the moment angle relationship of the individual joints of the lower limb (Serpell et al., 2012). Although joint stiffness measured using the torsional spring model is not the focus of this review, both this model and the spring-mass model have been used to quantify stiffness in individuals of all ages (Moran et al., 2023). Thus, the review will focus more on use of the spring-mass model used to measure stiffness during field-based fast-SSC tasks in girls.

Stiffness behaviour is based on Hooke's Law, where the amount of deformation that occurs in the 'spring' is proportional to the force acting on it. Larger external forces cause larger amounts of deformation, while the force-to-deformation ratio is mediated by the spring constant (i.e., the stiffness of an object) (Brughelli and Cronin, 2008a, Butler et al., 2003, McMahon et al., 2012). Without adequate stiffness, large forces subject the tissues to large strains. However, many SSC tasks are time-dependent, requiring the rebounding action to occur quickly. Therefore, stiffness is essential for facilitating the spring-like action necessary for efficient rebounding off the ground. For this to happen, strain is kept within a conservative range, preventing excessive stretching and tearing but allowing SSC action to occur faster (Mersmann et al., 2014, Mersmann et al., 2015, Mersmann et al., 2016, Waugh et al., 2017). Understanding the distinction between the various forms of global stiffness can help elucidate the relationship between applied forces and the corresponding deformation during fast-SSC tasks like reactive jumping and sprinting.

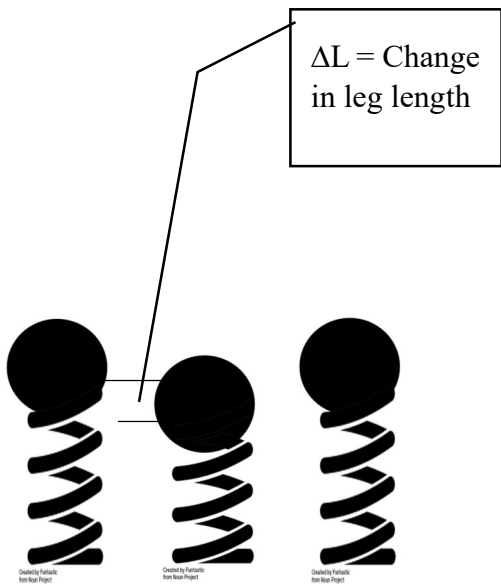


Figure 2.1. The spring-mass model during vertical sub-maximal hopping (Funtastic, 2024)

2.2.1 Vertical stiffness

Vertical stiffness describes how force is attenuated over the vertical displacement of the center of mass, using the spring-mass model (Brughelli and Cronin, 2008a, Butler et al., 2003, Brauner et al., 2014). Vertical stiffness does not correspond directly to one physical spring, as is the case with tendon stiffness. Instead, it describes the ability of all of the musculoskeletal elements in the lower body to control the vertical motions of the center of mass in response to an applied force (Farley and Gonzalez, 1996, Yin et al., 2020). During the ground contact phase of fast-SSC tasks, higher levels of vertical stiffness will increase the resistance to downward displacement of the body's center of mass (Waxman et al., 2018, Butler et al., 2003, Brughelli and Cronin, 2008a).

Vertical stiffness is commonly measured during sub-maximal vertical hopping because it is an energy efficient movement which limits movement in the horizontal and lateral directions (Maloney and Fletcher, 2018). Vertical-only movement results in equal displacement of the center of mass and leg, making vertical stiffness and leg stiffness equivalent (McMahon and Cheng, 1990, Farley and Gonzalez, 1996). Furthermore, throughout the literature these terms are often used interchangeably. During vertical movements like sub-maximal hopping, vertical stiffness is measured by determining the ratio of maximal vertical force to peak vertical displacement of the center of mass (Beerse and Wu, 2016). Measuring vertical stiffness in this manner requires force plates to directly measure peak vertical ground reaction force and estimate vertical acceleration to determine the displacement of the center of mass (Moresi, 2011). In the absence of a force plate, vertical stiffness has been measured using various technologies that record contact time and flight time. These include mobile contact mats (Lloyd et al., 2009), footswitch devices (Lloyd et al., 2012a), and floor-level optical measurement devices with infrared light barriers (Mattes et al., 2014). The recorded contact time, flight time, and body mass are used to calculate vertical stiffness using the method outlined by Dalleau et al. (2004) in adults. This method of calculating vertical stiffness has been deemed valid and reliable in girls (Lloyd et al., 2009, De Ste Croix et al., 2017).

In Equation 1, M = body mass, π = the half period of the sine wave, T_f = flight time, T_c = contact time, K_{vert} = vertical stiffness.

$$K_{\text{vert}} = [M * \pi (T_f + T_c)] / T_c^2 [(T_f + T_c / \pi) - (T_c / 4)]$$

Equation 1

2.2.1.1 Vertical stiffness in Girls

Vertical stiffness has been found to play a crucial role for both enhancing performance and mitigating injuries by preventing excessive displacement of the center of mass during fast-SSC tasks (De Ste Croix et al., 2018, Waxman et al., 2018). Among girls around the age of 16, those exhibiting greater vertical stiffness during unilateral sub-maximal hopping demonstrated significantly reduced contact time, prolonged flight time, increased peak vertical ground reaction force, and larger ankle dorsiflexion moments compared to girls with lower vertical stiffness levels (Waxman et al., 2018). Conversely, girls approximately 12 years of age have been found to produce high vertical stiffness relative to body weight (Bw/m), high rate of force development, and high levels of braking and propulsive power during drop jumping (Moeskops et al., 2020). These findings suggest that relative vertical stiffness is linked with the ability to produce force rapidly and efficiently during jumping.

The ability to produce force rapidly in a well-coordinated manner during ground contact differs between children and adults. For example, Beerse and Wu (2016), Beerse and Wu (2017), compared vertical stiffness characteristics in 5–11-year-old children and adults during unilateral sub-maximal hopping. They demonstrated significant differences between children and adults in absolute vertical stiffness (adults > children), the amount of center of mass displacement (adults > children), and how well vertical stiffness adjusted to changing frequencies (adults > children). Possible reasons may be children's diminished ability to use elastic energy in an efficient manner at the ankle joint, which alters their ability to hop in a spring like manner compared to adults (Beerse and Wu, 2022). The literature examining child-adult differences involves mostly mixed groups of boys and girls or boys alone. Therefore, further studies in girls are required to elucidate how vertical stiffness may help produce efficient, spring-like rebounding actions during fast-SSC tasks like drop jumping and hopping.

2.2.2 Leg stiffness

Vertical stiffness describes how force is attenuated in solely the vertical plane relative to the center of mass. Leg stiffness, in contrast, describes how force is attenuated in both the vertical and horizontal planes with respect to the change of the leg's displacement during locomotion (McMahon and Cheng, 1990, Maloney and Fletcher, 2018, Yin et al., 2020). During running, the leg must resist the vertical force of gravity as the body descends towards the ground following the flight phase. Simultaneously, the leg must withstand the horizontal braking forces generated when it lands in front of the body (Arampatzis et al., 1999, Brughelli and Cronin, 2008a, Hobara et al., 2010, Wang et al., 2015, McMahon et al., 2012). Specifically, during ground contact, the leg travels from a position in front of the center of mass at initial touchdown to underneath the center of mass during mid-stance. As it does so, the ground reaction force rises and then peaks at mid-stance, coinciding with the peak in vertical displacement of the center of mass and compression of the leg (Brughelli and Cronin, 2008a, Farley and Gonzalez, 1996). Leg stiffness during running can be determined using a force plate and then calculating the ratio between maximal force and change in leg length (Farley and Gonzalez, 1996). Alternatively, leg stiffness can be determined without a force plate using a footswitch or floor-level optical measurement devices with infrared light barriers, using the method that Morin et al. (2005) outlined. In Equation 2, F_{\max} = maximal force, ΔL = change in leg length, M = mass, g = acceleration due to gravity, T_f = flight time, T_c = contact time, v = velocity, and Δy = center of mass displacement, K_{leg} = leg stiffness.

$$K_{\text{leg}} = \frac{F_{\max}}{\Delta L}$$
$$F_{\max} = Mg \frac{\pi}{2} \left(\frac{T_f}{T_c} + 1 \right)$$
$$\Delta L = L - \sqrt{L^2 \left(\frac{vT_c}{2} \right)^2 + \Delta y}$$

Equation 2

2.2.2.1 Leg stiffness in girls

Leg stiffness has been evaluated in girls during vertical sub-maximal hopping (De Ste Croix et al., 2018, De Ste Croix et al., 2017, Eiling et al., 2007, Lehnert et al., 2020, Moeskops et al., 2018a, Millett et al., 2018) and vertical maximal hopping (Bradshaw et al., 2006, di Cagno et al., 2013, İnce, 2019, Laffaye et al., 2016, Mattes et al., 2018, Radu et al., 2015). These studies were able to highlight key features of leg stiffness behaviour. For example, De Ste Croix et al. (2017) discovered that leg stiffness under fatigued conditions is higher in older girls (U17) compared to younger girls (U13) during bilateral sub-maximal hopping at 2.5 hertz (Hz). The frequency, measured in Hz, represents the cued speed that aids in controlling hopping (Maloney and Fletcher, 2018). The finding by De Ste Croix et al. (2017) may be relevant when evaluating the injury-mitigating ability of leg stiffness during fast-SSC tasks. During these tasks, leg stiffness is associated with the high rate of force production necessary to respond quickly to tasks with high loading rates, like single-leg jump landings (Waugh et al., 2013).

Another feature of leg stiffness is the sex difference during fast-SSC tasks. While jump landing ability has been shown to differ between girls and boys (Quatman et al., 2006), so too have levels of leg stiffness. For instance, Lehnert et al. (2020), evaluated absolute and relative leg stiffness differences between girls and boys during bilateral sub-maximal hopping at 2.5 Hz. They demonstrated significant differences between the ages of 13-16 for both absolute and relative leg stiffness, where girls exhibited lower levels of leg stiffness compared to boys. Potential explanations for variations in leg stiffness have been proposed to stem from disparities in body size and the capacity to generate force, (Waugh et al., 2012) as well as differences in hormone concentrations (Eiling et al., 2007). Although the effects of the menstrual cycle are outside the scope of this review, leg stiffness during unilateral sub-maximal hopping at 2.2 Hz was shown to be significantly lower during the ovulatory phase compared to the first day of menses and day seven of the follicular phase in 16-year-old girls (Eiling et al., 2007).

A final leg stiffness feature described by researchers is the adjustable nature of leg stiffness where individuals from different athletic backgrounds express varying amounts of leg

stiffness for a given fast-SSC task. For example, Millett et al. (2018) evaluated leg stiffness in 17-year-old Netball girls during sprinting. Netball girls in this study differed from physically active girls in levels of leg stiffness, peak vertical ground reaction force, and contact time. This difference suggests an activity-related influence on leg stiffness. However, no researchers have compared leg stiffness during different fast-SSC tasks in girls like the studies that have been conducted in boys (Lloyd et al., 2012a).

Many uncertainties persist regarding leg stiffness in girls, including how leg stiffness affects sprinting and sub-maximal hopping across maturation or between maturity stages. Addressing these gaps will enhance our understanding of the difference in leg stiffness between different maturity stages and more appropriately, inform training and injury prevention strategies for girls during various SSC tasks.

2.2.3 Joint stiffness

Joint stiffness describes the change in joint angle in response to a force at the joint (Ford et al., 2010). Joint stiffness stabilizes the joint against externally imposed forces that occur during fast-SSC tasks like vertical hopping or sprinting (Farley et al., 1998, McMahon et al., 2012, Serpell et al., 2012). Joint stiffness is described by the torsional spring model, which highlights the stiffness contribution of the hip, knee, and ankle joints during movement (Serpell et al., 2012, Maloney and Fletcher, 2018). Knowledge of these contributions can help identify how a joint may adjust its level of stiffness when task conditions change. An example of this occurrence is how ankle stiffness augments more than other joints when transitioning from sub-maximal hopping to maximal hopping (Farley and Morgenroth, 1999).

Joint stiffness functions more efficiently when joints are moderately flexed upon ground contact, rather than being excessively extended. Overly rigid joint positions pose a greater risk to the bony structures of the lower limbs (Butler et al., 2003, Wang et al., 2015). Likewise, excessive collapse toward the ground due to inadequate muscular torque may not

effectively resist externally applied forces (Wang et al., 2015, DeVita and Hortobagyi, 2000). These overly flexed positions are less problematic during non-time-dependent tasks in sports, such as landing from a jump in figure skating. However, during time-dependent tasks, like the ground contact phase in sprinting, a stiffer joint can attenuate force in a shorter amount of time (Meyers et al., 2016). Therefore, an optimal level of joint stiffness is required to respond to higher externally applied forces and higher rates of loading (Ford et al., 2010). Calculations for determining joint stiffness are exhibited in Equation 3, where ΔM = change in joint moment and $\Delta\Theta$ = change in joint angle (Butler et al., 2003). Joint stiffness requires the use of a force plate and motion capture for quantification (Brughelli and Cronin, 2008a).

$$K_{\text{joint}} = \frac{\Delta M}{\Delta\Theta}$$

Equation 3

2.2.3.1 Joint stiffness in girls

Researchers have investigated joint stiffness in girls during unilateral vertical drop jumping, horizontal drop jumping, unilateral countermovement jumping (Millett et al., 2016) and during bilateral drop jumping using force plates and motion capture devices (Ford et al., 2010, Taylor et al., 2017, Christoforidou et al., 2017). Millett et al. (2016) demonstrated how individual joint stiffness levels can significantly differ between athletes of varied athletic backgrounds, even if there are no overall leg stiffness differences. More precisely, to control and coordinate the ground contact phase of drop jumping, running athletes were able to use a modulation strategy that relied on higher contributions of hip and ankle stiffness. Conversely, the control group relied on knee and ankle stiffness. Sport related differences were also discovered by Taylor et al. (2017), during an analysis of joint stiffness in soccer and basketball players. They reported increased hip and knee stiffness contributions during lateral bilateral countermovement jumping compared to soccer players. Finally, Christoforidou et al. (2017) conducted a comparison of knee joint stiffness between 10-year-old female gymnasts and an 11-year-old untrained control group. They discovered that knee joint stiffness was significantly higher in gymnasts. Gymnasts may have experienced structural changes in the musculotendinous tissues due to their gymnastics training. Together,

these studies underscore the impact of sport-specific loading on stiffness, particularly in girls. Due to the varying loading strategies employed by athletes in different sports, varying biomechanical strategies with unique patterns of joint stiffness may be employed to optimize performance. The demands places on athletes of different sports may vary the influence on a given joint. Knowledge of these varying strategies may inform training and injury prevention programs by encouraging more targeted approaches.

There were no studies that compared maturational differences in joint stiffness between all stages of development. Furthermore, there were no studies in girls where joint stiffness during sprinting was evaluated. Addressing these gaps would provide a more thorough understanding of the maturational-related differences in joint stiffness during a range of fast-SSC tasks. Notably, determining joint stiffness requires expensive, time-consuming measurement devices that are not always accessible to a wide range of researchers or practitioners and, therefore, are less researched than the other stiffness measures reviewed.

2.3 STIFFNESS CHANGES WITH GROWTH AND MATURATION

2.3.1 Time course of adaptation of global stiffness

Fast-SSC tasks like sprinting and hopping in youth, benefit from spring-like applications of force that are mediated by stiffness (Clark and Weyand, 2014, Pedley et al., 2021). During these actions, appropriate levels of stiffness allow the eccentric and concentric phases to exhibit energy-efficient, symmetrical force-time profiles during the ground contact phase (Moeskops et al., 2020). Symmetrical rebounding, crucial for energy efficiency, is marked by the alignment of peak vertical ground reaction force with peak displacement of the body's center of mass or leg compression (Clark and Weyand, 2014, Moeskops et al., 2020, Pedley et al., 2021). However, the ability of stiffness to mediate spring-like force application develops naturally throughout childhood and adolescence (Moeskops et al., 2020). Furthermore, there is a lack of clarity regarding stiffness development in girls compared to boys, with most studies concentrating on stiffness development by age during maximal and

sub-maximal hopping (Laffaye et al., 2016, Lehnert et al., 2020) or by maturity status up to the pubertal stage in girls during drop jumping (Moeskops et al., 2020).

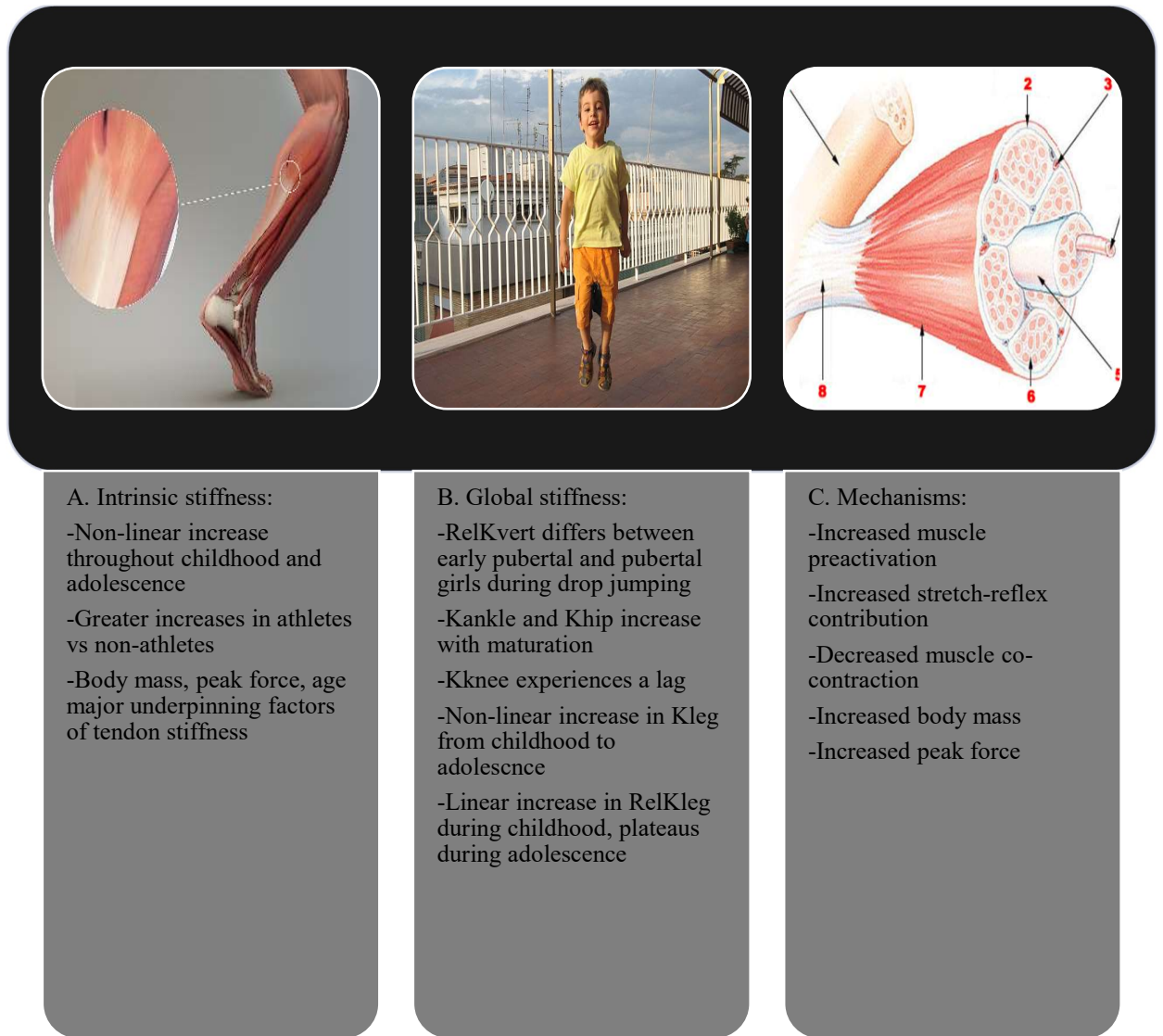
In boys during childhood, researchers have observed a linear increase in absolute and relative leg stiffness during sub-maximal hopping. Following this rise, a substantial decline has been observed between ages 10.86-11.56 years for absolute leg stiffness, and between 10.86 and 12.59 years of age for relative leg stiffness. The commencement of these declines occur approximately 12-18 months prior to PHV (Lloyd et al., 2011b). However, following PHV, absolute leg stiffness exhibited a linear increase once more, whereas relative leg stiffness underwent a plateau. These results align with the longitudinal study by Meyers et al. (2016), which illustrated that relative leg stiffness during sprinting exhibited a more significant increase in the pre-peak height velocity (pre-PHV) group compared to boys who had already experienced PHV. Overall, these results suggest that most relative leg stiffness development occurs during childhood, while absolute leg stiffness continues to rise throughout childhood and adolescence. This relative leg stiffness pattern may be attributed to differential leg and trunk growth, impacting motor coordination, as well as fluctuations in body mass or composition, affecting relative force production capability (Lloyd et al., 2011b, Laffaye et al., 2016).

There are limited studies where the maturity-related differences in stiffness have been assessed in girls. Moeskops et al. (2020) described the maturity-related difference in relative vertical stiffness during drop jumping between early pre-pubertal and pubertal girls. They demonstrated that relative vertical stiffness (BW/m) was significantly higher in pubertal girls compared to early pre-pubertal girls, but not between late pre-pubertal to pubertal girls or between early pre-pubertal to late pre-pubertal girls. The significant difference between pubertal and early pre-pubertal girls may have contributed to the higher jump height in this maturity group. This finding highlights the impact of maturity-related vertical stiffness development on high impact jumping performance. It also emphasizes the importance of considering normalization techniques when assessing vertical stiffness to account for variations in body morphology and size across different maturity stages.

Additionally, Ford et al. (2010) examined joint stiffness changes over consecutive years, differences between maturity groups, and differences in joint stiffness between maturity groups (pubertal, post pubertal). They reported that absolute and not relative (body mass) ankle, knee, and hip stiffness increased significantly with time in the pubertal group. However, they determined that maturation status only had a significant effect on the changes that occurred in ankle and hip joint stiffness. This was indicated by the significant changes in ankle and hip stiffness in the pubertal but not post pubertal group. These findings reflect a disruption in knee joint stiffness development during the post pubertal period and that body mass increases during adolescence influence joint stiffness. It is plausible that disruption in knee joint stiffness development leads to adverse effects concerning the attenuation of force at the knee joint to prevent excessive collapse. To elaborate, if joint stiffness were high at the ankle and hip but not at the knee, it might result in a significant excursion at the knee joint compared to other joints, potentially exposing it to risk during the landing phase of fast stretch-shortening cycle (SSC) tasks (Beerse and Wu, 2022, Russell et al., 2007).

Stiffness mediated SSC performance may vary depending on the task (Maloney and Fletcher, 2018). Task specific development in absolute and relative leg stiffness has been examined by age in girls 11-19 years-old (Laffaye et al., 2016, Lehnert et al., 2020). Laffaye et al. (2016) demonstrated that absolute leg stiffness increased non-linearly during maximal hopping with a significant increase between ages 15 and 16 and a decrease between ages 17-18. Furthermore, they reported that relative leg stiffness exhibited a plateau during this period (Laffaye et al., 2016). Conversely, during their assessment of leg stiffness across consecutive seasons in 13-year-old and 15-year-old girls, Lehnert et al. (2020) noted an age-related plateau in absolute leg stiffness. Moreover, they observed a substantial age-related decrease (-16.1%) in relative leg stiffness during sub-maximal hopping in 15-year-old girls. Meanwhile, the 13-year-old girls maintained absolute and relative leg stiffness. These findings suggest that variations exist in the timing of increases and decreases of absolute and relative leg stiffness in girls with varying tasks. This concurs with Lloyd et al. (2011b), who suggested that different expressions of SSC function may evolve uniquely over time in boys. This evolution reflects the interaction between growth, maturation-related changes, and the diverse demands of the respective tasks.

Laffaye et al. (2016) proposed that substantial increases in body fat could account for the notable decrease in relative leg stiffness. Specifically, the heightened fat levels might have adversely impacted relative force production and thus, the ratio of force to deformation (Laffaye et al., 2016, Moresi et al., 2015). A poor force to deformation ratio is characterized by an early peak in the vertical ground reaction force that does not coincide with the peak deformation. This discrepancy leads to an asymmetrical force-time profile between the downward and propulsive phases during ground contact (Moeskops et al., 2020, Pedley et al., 2021). Laffaye et al. (2016) reported that this ratio is more favorable in older girls and boys, whereas Pedley et al. (2021) demonstrated a significantly larger ratio in post-pubertal girls compared to pre-pubertal and pubertal girls. Therefore, girls may potentially benefit from stiffness measurement tasks that entail more energy-efficient movements, which promote an appropriate force to deformation ratio such as sub-maximal hopping. Additionally, this movement poses a reduced risk of movement in non-vertical planes, which is essential for being able to calculate vertical and leg stiffness (Brughelli and Cronin, 2008a). Understanding the patterns of global stiffness differences between maturity and age groups aids in identifying optimal timings and strategies for implementing targeted training to enhance stiffness development. Figure 2.2 summarizes the natural development of global stiffness.



A. Intrinsic stiffness:

- Non-linear increase throughout childhood and adolescence
- Greater increases in athletes vs non-athletes
- Body mass, peak force, age major underpinning factors of tendon stiffness

B. Global stiffness:

- RelKvert differs between early pubertal and pubertal girls during drop jumping
- Kankle and Khip increase with maturation
- Kknee experiences a lag
- Non-linear increase in Kleg from childhood to adolescence
- Linear increase in RelKleg during childhood, plateaus during adolescence

C. Mechanisms:

- Increased muscle preactivation
- Increased stretch-reflex contribution
- Decreased muscle co-contraction
- Increased body mass
- Increased peak force

Figure 2.2. Maturity-related changes in stiffness- Intrinsic stiffness (A), global stiffness (B), mechanisms (C).

- A. (Waugh et al., 2012, Chalatzoglidis et al., 2021, Manu, 2018)
- B. (Laffaye et al., 2016, Lehnert et al., 2020, Moeskops et al., 2020, Ford et al., 2010, Zangrilli, 2007)
- C. (Lloyd et al., 2012a, Oliver and Smith, 2010, Christoforidou et al., 2017, Grosset et al., 2008, Lambertz et al., 2003, Waugh et al., 2012, Chalatzoglidis et al., 2021, Kemp, 2007)

2.3.2 Time course of adaptation of intrinsic stiffness

Intrinsic forms of stiffness mediate the SSC, by providing resistance to changes in length under load (Latash and Zatsiorsky, 1993, Waugh et al., 2012). During this process, elastic energy is stored in the lengthened tissues which then potentiates subsequent muscle shortening (Blickhan, 1989, Komi, 2000). Musculotendinous stiffness, the resistance to length change provided by the muscles and tendons, has mostly been evaluated in studies where girls and boys were pooled together to assess age-related differences (Grosset et al., 2005b, Lambertz et al., 2003, Grosset et al., 2007, Waugh et al., 2012, Waugh et al., 2013, Waugh et al., 2014, O'Brien et al., 2010a). For example, Waugh et al. (2012) examined the dimensional and material characteristics of the Achilles tendon among different age groups. They reported larger effect sizes in Achilles tendon stiffness when children were compared to adults than between children aged 5-7 years and 8-10 years. Irrespective of age variances, both absolute and relative Achilles tendon stiffness were accounted for by factors such as body mass, peak force, and age (age effect only when adults were included in the analysis). This underscores the influence of mechanical loading on tendon stiffness. This finding regarding mechanical loading agrees with the longitudinal study by Chalatzoglidis et al. (2021), who examined the maturational changes in Achilles tendon stiffness in athletes and non-athletes. They demonstrated a greater degree of increase in relative Achilles tendon stiffness in athletes compared to non-athletes with increasing maturation. The findings by Waugh et al. (2012) and Chalatzoglidis et al. (2021) indicate how developmental increases in body mass, strength, and activity-related loading influence the natural development of musculotendinous stiffness in youth. The rise in musculotendinous stiffness during childhood and adolescence is linked to alterations in tendon and muscle properties, including dimensional and material changes, such as improvements in collagen microstructure. Additionally, neural adaptations, such as increased muscle preactivation, contribute to stiffness enhancement. These adaptations aim to accommodate the increase in body mass and muscle strength, thereby preserving tendon function and health (Waugh et al., 2013, Waugh et al., 2014, Mersmann et al., 2015, Mersmann et al., 2017a). However, it is unknown how stiffness at the tissue level changes with maturation or differs between maturity stages in girls only. Future research should include investigations into the properties that mediate intrinsic stiffness increases throughout childhood and adolescence in girls only. Figure 2.2 summarizes the natural development of intrinsic stiffness.

2.3.3 Determinants of stiffness increase throughout childhood and adolescence

Stiffness is essential for efficiently transferring force from muscles to bones through tendons, enhancing energy efficiency during stretch-shortening cycle (SSC) movements (Waugh et al., 2013). In fast-SSC movements, tendons undergo initial lengthening and resistance to deformation, reaching a point of 'critical tension,' after which lengthening, and resistance occur in actin/myosin cross-links. While a compliant strategy involving larger muscle length changes can store substantial elastic energy and produce significant work during tasks with flexible timing (provided contraction time permits), it may be unsuitable for fast-SSC tasks. Significant muscle length changes can result in high metabolic costs, fatigue, and a decreased rate of force development (Komi and Gollhofer, 1997). For example, excessive muscle lengthening occurs during slower, sub-maximal hopping frequencies, leading to longer contact times and greater collapse towards the ground. This results in more energy dissipation than faster hopping frequencies, which have shorter ground contact times and smaller collapse towards the ground. Therefore, if tendons provide most of the required resistance to deformation, they can reduce the metabolic cost of movement and enhance force production during the shortening phase of SSC tasks (Komi and Gollhofer, 1997, Turner and Jeffreys, 2010).

The tendon's ability to withstand the required resistance to length change is facilitated by the muscles' capacity to maintain high tension levels with minimal length alteration (Horita et al., 2002, Komi and Gollhofer, 1997). Specifically, elevated levels of muscular activation can restrict muscle stretching and optimize tendon utilization. For example, during activities like sprinting, intense muscle activity enables tendons to resist changes in length and store elastic energy crucial for enhancing force during the propulsive phase (Komi and Gollhofer, 1997, Turner and Jeffreys, 2010, Sahrom et al., 2013).

The natural progression of stiffness is influenced by the growth and maturation of tendon dimensional properties (e.g., cross-sectional area), material properties (e.g., Young's Modulus), and their interplay with neuromuscular factors (including muscle activation and stretch reflexes). However, the specific role of tendons in mediating stiffness exclusively in

girls remains underexplored. Given how tendon changes during childhood differ from those during adolescence (Tumkur Anil Kumar et al., 2021, Radnor et al., 2017), reviewing the role of tendons in stiffness mediation is warranted. Understanding the evolution and interaction of these factors is crucial for grasping the natural progression of stiffness and optimizing training-induced enhancements in stiffness. The tendon-related changes that mediate stiffness will be the focus of this remaining section. Figure 2.2 summarizes the regulating mechanisms of stiffness.

2.3.3.1 Tendon material properties

Tendon stiffness relies on the coordination of tendon fibrils to resist changes in length from applied force during athletic movements (Vaughn et al., 2013). The organizational elements of the tendon microstructure that influence tendon stiffness include collagen fibril diameter, packing density, cross-linking, and crimping (Bailey and Paul, 1999). However, methods for assessing tendon microstructure are invasive and impractical for youth populations (Parry et al., 1978, Arya and Kulig, 2010). Instead, the determination of Young's modulus provides a more feasible determination of the material properties or microstructure of the tendon's collagen framework (Arya and Kulig, 2010, Mersmann et al., 2014, Radnor et al., 2017).

To calculate Young's modulus, one must ascertain the slope of the stress/strain relationship of the tendon. Here, stress denotes tendon force relative to cross-sectional area (CSA), while strain represents the tendon's length change under load relative to resting length (Mersmann et al., 2014, Mersmann et al., 2015, Mersmann et al., 2016, Chalatzoglidis et al., 2021, O'Brien et al., 2010a, Kruse et al., 2017). Therefore, Young's modulus represents the intrinsic stiffness of the material in tension (Huda, 2022). Disproportionate increases in tendon width relative to length throughout childhood and adolescence will augment tendon stiffness, while the opposite decreases tendon stiffness (O'Brien et al., 2010a, Vaughn et al., 2012). When both dimensions increase proportionately, and tendon stiffness still rises, it suggests a change in Young's modulus as the cause (Mersmann et al., 2014, Kruse et al., 2017). Growth is more stable during childhood, and proportional increases in tendon width and length occur alongside steady body mass increments. Given the smaller magnitude of tendon dimensional

changes in children, changes in Young's modulus may be the more favorable cause of tendon stiffness increases during childhood (Naughton et al., 2000, Waugh et al., 2012, Mersmann et al., 2015).

2.3.3.2 Dimensional and mechanical properties of the tendon

The natural development of stiffness during adolescence may rely more on tendon dimensional changes and their effect on tendon mechanical qualities, such as stress (Mersmann et al., 2015). Examples of dimensional changes include tendon cross-sectional area (CSA) and length (Mersmann et al., 2014, O'Brien et al., 2010a, Chalatzoglidis et al., 2021). There is a non-linear increase in tendon CSA from childhood to adolescence, with a larger rate of increase in CSA during adolescence compared to childhood (Mersmann et al., 2015, O'Brien et al., 2010b, O'Brien et al., 2010a, Waugh et al., 2012, Neugebauer and Hawkins, 2012). The enlargement of tendon CSA is attributed to the thickening of tendon fibrils aligned in parallel. This increased CSA reduces the force exerted per unit area, termed stress. Excessive stress reflects excessive load on the tendon, which can lead to damage (Mersmann et al., 2014, Mersmann et al., 2015, Radnor et al., 2017). Notably, there is an escalation in tendon stress during childhood but a subsequent decline during adolescence (Mersmann et al., 2014, Mersmann et al., 2015). Adequate increases in tendon CSA can enhance tendon stiffness, facilitating improved force transmission to the bone and enabling faster and more efficient muscle action (O'Brien et al., 2010b, Radnor et al., 2017). Therefore, augmented CSA is a pivotal adaptation that reduces stress, augments tendon stiffness, enhances performance and protects against injury.

Dimensional properties also include measurements of tendon resting length and their effect on mechanical properties like elongation and strain (Mersmann et al., 2014). Elongation represents the change in length that occurs under load, whereas strain represents the ratio of the change in length to its original (resting) length, when subjected to an external load (Waugh et al., 2012, Huda, 2022). It has been demonstrated that tendons with longer resting length are likely to be less "stiff" due to the increased distance over which force must be transferred from the muscle to the bone (O'Brien et al., 2010b, Waugh et al., 2013, Waugh et

al., 2014, Radnor et al., 2017). However, tendon length remains unchanged during childhood (Pentidis et al., 2019), increases during early adolescence (Neugebauer and Hawkins, 2012, Chalatzoglidis et al., 2021) then stabilizes during mid-to late adolescence (Mersmann et al., 2015, Mersmann et al., 2016). Therefore, increases in tendon length during early adolescence may contribute to the declines in tendon stiffness observed during puberty in both girls and boys (Chalatzoglidis et al., 2021).

A parallel increase in tendon elongation accompanies the significant increase in tendon resting length during early adolescence (Chalatzoglidis et al., 2021, Waugh et al., 2012, Neugebauer and Hawkins, 2012). This parallel increase signifies that the elongation and strain do not change significantly throughout childhood and adolescence (Waugh et al., 2012, O'Brien et al., 2010a, Mersmann et al., 2016). However, when a tendon is under load during a fast-SSC task like hopping, tendon strain is often kept within a limited range by increasing tendon stiffness (Waugh et al., 2012, O'Brien et al., 2010a). This indicates that tendons tend to react to loading within an optimal range of length change, rather than undergoing excessive deformation, thereby reducing the risk of injury (Mersmann et al., 2015, Waugh et al., 2012, Waugh et al., 2013, Brughelli and Cronin, 2008a, Serpell et al., 2012). These insights underscore the importance of considering both the dimensional and mechanical aspects of tendons in the context of growth maturation and their implications for injury prevention and athletic performance optimization during fast-SSC tasks.

2.3.4 Neurological modulation and influence of stiffness

The interaction of neuromuscular qualities, such as muscle preactivation, antagonist co-contraction, and the contribution of stretch reflexes, contribute to stiffness regulation during fast-SSC tasks (Radnor et al., 2017). Muscle preactivation is a preparatory mechanism of stiffness control, while antagonist co-contraction and the stretch-reflex are feedback control mechanisms. Together, these mechanisms influence stiffness and thus, the relationship between force production and force application (Waugh et al., 2013).

2.3.4.1 Motor-unit activation and muscle preactivation

Prior to ground contact during fast-SSC tasks, muscle activation influences stiffness mediated force application. Higher levels of muscle activation prior to ground contact will limit the amount of MTU stretch and time required to build up maximal tension during the eccentric phase (Dotan et al., 2012, Taube et al., 2012, Oliver et al., 2014, Hobara et al., 2008, Moresi, 2011). The improved efficiency of force development during a task like sprinting will improve the ability to resist leg collapse upon ground contact, improve the transition from the eccentric phase to the concentric phase and shorten contact time (Sahrom et al., 2013, Patikas, 2014, Brughelli and Cronin, 2008a, Meyers et al., 2017a, Oliver et al., 2014, Oliver and Smith, 2010, Taube et al., 2012, Farley and Gonzalez, 1996).

Children have a reduced ability to activate their motor units and to preactivate their muscles in anticipation of ground contact (Lazaridis et al., 2010, Oliver and Smith, 2010). This reduced capability has been shown to significantly decrease muscle activity both at the moment of, and throughout, ground contact, thereby impairing children's ability to use a "stiff" ground contact strategy (Radnor et al., 2017, Lloyd et al., 2012a, Oliver and Smith, 2010, Bobbert et al., 1987). Given this diminished ability, children are more reactive instead of preactive when applying force to the ground. However, the ability to preactivate muscles improves with age during childhood (Oliver and Smith, 2010, Lloyd et al., 2012a). Moreover, most studies have compared boys and men (Oliver and Smith, 2010, Oliver et al., 2014, Lazaridis et al., 2010), and limited studies exist involving girls (Christoforidou et al., 2017). For example, Lloyd et al. (2012a) analyzed normalized electromyography data during maximal hopping. They revealed that 15-year-old boys produced significantly greater levels of Soleus preactivation in comparison to both nine- and 12-year-olds. This suggests that as children become older, they are more reliant on preactivation prior to ground contact and can more appropriately generate a "stiff" ground contact strategy. Additionally, Christoforidou et al. (2017) evaluated force-time variables during drop jumping in 9-12 year-old female gymnastics compared to untrained girls. They reported significantly higher preactivation levels in the vastus lateralis and lateral gastrocnemius when drop jumping from 20 cm, 40 cm, and 60 cm. Higher preactivation allowed gymnasts to have a significantly shorter eccentric phase at 20 cm and 60 cm, significantly higher impulse at 60 cm, significantly

higher normalized peak vertical ground reaction force at all three drop heights, and higher knee joint stiffness at all three drop heights. These findings emphasize that improvements in muscle preactivation are essential to the ability to control and coordinate the ground contact phase of fast-SSC tasks. The findings may also suggest the role of activity-related loading in building the ability to preactivate muscles before ground contact. The ability to arrest large forces in a shorter time, reduces ground contact time and hastens the eccentric to concentric transition during fast-SSC tasks. These improvements may contribute to the improved SSC function seen with age in children (Brughelli and Cronin, 2008a, Laffaye et al., 2016, Bradshaw et al., 2006, Radnor et al., 2017).

Other researchers have evaluated musculotendinous stiffness and muscular activation in children, where it was found that musculotendinous stiffness increases with muscular activation in pre-pubertal children (Paiva et al., 2012, Lambertz et al., 2003, Lambertz et al., 2013b). Moreover, younger pre-pubertal children require a higher activation level to uphold a given torque level compared to older children and adults (Lambertz et al., 2003). This reduced neuromuscular efficiency in younger children may suggest a decline in the stiffness-torque relationship as children age (Lambertz et al., 2003, Paiva et al., 2009), underscoring the importance of considering activation levels. Yet, when musculotendinous stiffness is adjusted relative to muscle activation to determine the tendon's intrinsic elastic properties (Lambertz et al., 2003), stiffness notably increases with age in children, although it remains considerably lower compared to adults (Paiva et al., 2009, Lambertz et al., 2003). Considering the importance of motor unit activation and muscle preactivation during landing, the decreased levels observed in children could potentially diminish stiffness and, consequently, the force-attenuating behavior needed to manage loading during the ground contact phase of fast-SSC tasks (Russell et al., 2007).

2.3.4.2 Antagonist co-contraction

Antagonistic co-contraction describes the extent to which antagonist muscles contract simultaneously with the agonist muscles around a joint (Falk et al., 2009, Lazaridis et al., 2010). Co-contraction can provide stability to a joint, especially with higher intensity tasks

like maximal hops compared to sub-maximal hops (Lloyd et al., 2012a). However excessive levels of antagonist co-contraction can result in increased energy cost and reduced net force output of the agonist muscle. This less efficient neuromuscular strategy leads to lower intrinsic stiffness, and increased ground contact times during fast-SSC tasks (Dotan et al., 2012, Oliver and Smith, 2010, Patikas, 2014, Tumkur Anil Kumar et al., 2021).

The level of co-contraction tends to be higher in younger children compared to older children (Grosset et al., 2008, Lambertz et al., 2003) and adults (Russell et al., 2007, Oliver and Smith, 2010). The age differences are due to overactivation of motor units for a given force level (Lambertz et al., 2003), overactivation of the Golgi tendon organ, and lower levels of intermuscular coordination (Tumkur Anil Kumar et al., 2021). Reductions in antagonist co-contraction with growth and maturation allows for more efficient muscle contraction where the agonist muscle contracts forcefully and the antagonist muscle decreases its contribution, thus increasing net force output and stiffness (Tumkur Anil Kumar et al., 2021).

2.3.4.3 Reflex contribution

Reflex mediated muscle activity is integral to the neural control of stiffness during the ground contact phase of fast-SSC tasks (Oliver et al., 2014, Oliver and Smith, 2010). The most appropriate example is the stretch-reflex response, which involves spinal reflexes and supra spinal reflexes, which consist of a rapid muscle action in response to the detection of a rapid muscle stretch. The rapid muscle stretch activates a special sensory cell called a muscle spindle which communicates with motor neurons to cause a muscle action. The stretch-reflex response prevents overstretching of the muscle-tendon unit and helps build and maintain the muscle tension necessary to allow short and forceful muscle-tendon unit reversal during ground contact (Cronin et al., 2011, Taube et al., 2012, Komi and Gollhofer, 1997, Grosset et al., 2007, Oliver and Smith, 2010).

Stretch reflexes are characterized by both amplitude and latency. Stretch-reflex amplitude refers to the magnitude of the stretch-reflex, while stretch-reflex latency refers to the rapidness of the response to muscle stretch (Cronin et al., 2011, Taube et al., 2012). Reflex

latency during hopping studies is often described by the percentage of the total muscle activity during the entire ground contact period. To be more precise, the time window of 31-60 ms post ground contact signifies short-latency spinal reflex activity, involving the spinal cord only, characterized by monosynaptic rapid motor responses. The interval of 61-90 ms post ground contact involves supra spinal intermediate latency reflexes, influenced by higher brain function, exhibiting polysynaptic varied motor responses. Lastly, the period from 91-120 ms post ground contact encompasses supra spinal long-latency reflexes (Oliver et al., 2014, Oliver and Smith, 2010, Lloyd et al., 2012a).

Children rely on long latency stretch reflexes to regulate stiffness, while adults rely on short latency reflexes (Oliver et al., 2014, Oliver and Smith, 2010). The ability to use short latency reflexes augments adults' ability to control and coordinate the ground contact phase of fast-SSC tasks like sub-maximal hopping (Oliver and Smith, 2010). For example, Lazaridis et al. (2010) and Oliver and Smith (2010) assessed stretch-reflex activity of different lower limb extensor muscles of 9–12-year-old boys compared to men during drop jumping and sub-maximal hopping respectively. These researchers discovered that short latency reflex responses were significantly lower in boys compared to men. They also found that boys tended to show greater amounts of muscle activity in periods associated with longer-latency reflexes. As reasons for this discrepancy, the authors suggested that boys have less sensitive muscle spindles, more sensitive Golgi tendon organs (increased neuromuscular inhibition), and an overall diminished ability to raise their muscle activation during high intensity tasks. These factors resulted in longer time spent on the ground, causing force to build up over a longer period while in contact with the ground.

Finally, Lloyd et al. (2012a), assessed the reflex activity differences of lower limb extensor muscles in 9, 12 and 15-year-old boys during sub-maximal hopping. They reported that 9-year-old boys had significantly lower Soleus short latency reflex activity compared to 12- and 15-year-old boys. These findings suggest that the ability to leverage short latency reflexes to mediate leg stiffness increases with age, and higher reflex activity and shorter latency reflexes lead to greater leg stiffness, especially as the speed of hopping increases.

Stretch, reflexes and other neuromuscular mechanisms play a decisive role in the control of stiffness, especially with increasing age. There is a lack of studies solely assessing stretch-reflex activity in girls alone during SSC tasks like sub-maximal hopping. While girls may undergo a similar developmental process as boys in the stretch-reflex regulation of stiffness, further research focusing on girls is needed to explore this possibility fully.

2.4 STIFFNESS AND TRAINING

Various forms of training have been used to develop global and intrinsic stiffness in young girls, including strength training (Waugh et al., 2014, İnce, 2019), plyometric training (Katsikari et al., 2020, Sylvester et al., 2024), and combined training methods (Moeskops et al., 2022a, Moeskops et al., 2018a, De Ste Croix et al., 2018). The following sections discuss the efficacy of these training methodologies across various stages of maturity. A summary of the relevant training studies is presented in Table 2.1.

2.4.1 Strength training

Mechanical loading from growth and maturation related increases in body mass, strength, and sport related activity, prompt adaptations in the tendon dimensions (e.g., cross-sectional area) and intrinsic material composition (e.g., Young's modulus). It is these adaptations that explain the natural development of musculotendinous stiffness in youth (Waugh et al., 2012, Mersmann et al., 2017b, Chalatzoglidis et al., 2021, Moeskops et al., 2020). The adaptations resulting from imposed loading bolster the tendon's capacity to endure mechanical stress and uphold healthy function throughout its development. Over and above natural development, intentional efforts to further enhance stiffness can be pursued through strength training (Lloyd et al., 2014a, Behm et al., 2017, Kubo et al., 2007, Tumkur Anil Kumar et al., 2021, Mersmann et al., 2017b, Moran et al., 2023).

Waugh et al. (2014) examined the impact of strength training on Achilles tendon stiffness in pre-pubertal girls and boys aged 8.9 years. Results indicated a significant enhancement in

Achilles tendon stiffness compared to the control group following 10 weeks of bi-weekly plantar flexion exercises. However, there were no observed improvements in tendon cross-sectional area. Specifically, the experimental group exhibited a 28.5% increase in stiffness compared to 2.9% increase in the control group. It is possible that a change in Young's modulus, as well as improved neuromuscular efficiency were responsible for the stiffness development (Grosset et al., 2008, Lambertz et al., 2003, Dotan, 2016, Dotan et al., 2012, Waugh et al., 2012). In another study, İnce (2019) administered a strength training intervention with a group of 15-year-old volleyball girls twice a week for 6 weeks. The intervention, comprising Olympic weightlifting, likely resulted in a positive increase in leg stiffness (Reported Cohen's $d = 0.9$, 95% CI = 0.16, 1.6, large effect) as measured during maximal hopping. In contrast, the control group did not show significant improvements. It is possible that changes in leg stiffness were due to a combination of structural changes in the muscles and tendons, and neuromuscular changes like increased rate of force development and intermuscular coordination (Tumkur Anil Kumar et al., 2021, Behm et al., 2017, Lloyd et al., 2012d). Structural changes have been documented as a primary mechanism for stiffness changes during adolescence (Mersmann et al., 2017b, Mersmann et al., 2015, Mersmann et al., 2016). Based on findings from these two studies, strength training might serve as a suitable stimulus for improving stiffness, albeit through potentially distinct mechanisms in children compared to adolescents. Given the vast difference in training methods between İnce (2019) and Waugh et al. (2014), future studies are encouraged to investigate various forms of strength training in children and adolescents to determine the most suitable method for enhancing stiffness.

2.4.2 Plyometric training

Plyometric training involves reactive SSC movements (e.g., hopping and bounding) (Johnson et al., 2011, Moran et al., 2018b). Two studies have investigated the impact of plyometric training on global stiffness exclusively in young girls. *Firstly*, Katsikari et al. (2020) evaluated the effect of a 10-week, two-day per week plyometric training program in untrained 9–11-year-old pre-pubertal girls. This study targeted knee joint stiffness while drop jumping from 20 cm, 35 cm, and 50 cm. There were no significant changes reported for knee stiffness during drop jumping at either height but there was a significant increase in jump height. It

was suggested by Katsikari et al. (2020) that the lack of improvement in knee stiffness at all drop jump heights (Hedges' $g = -0.97-0.08$) was because the participants improved jump height through a strategy involving higher knee flexion and contact time. This compliant strategy meant that a higher active state and larger amount of elastic energy was built up in the muscle prior to the propulsion phase. However, this may have been accomplished at the expense of contact time (Turner and Jeffreys, 2010). Future studies could emphasize a specific ground contact strategy during plyometric exercises that involve short ground contact times while maintaining a safe and appropriate jump technique.

The findings by Katsikari et al. (2020) are contrary to (Sylvester et al., 2024), who evaluated the effect of an 8-week plyometric training intervention on absolute leg stiffness in post-PHV female volleyball players. Significant changes were reported in absolute leg stiffness during sub-maximal hopping at 2.5 Hz on the dominant leg (Mean difference = 4.4%, CV% = 3.89 %). It may be that stiffness adaptations measured during sub-maximal hopping are achieved easier than those during drop jumping. This postulation is supported by Ford et al. (2010), who reported that maturation-related knee joint stiffness development may lag ankle and hip joint stiffness development. If a delay in knee stiffness does impact the capacity to achieve training-related gains in leg stiffness, then girls might benefit from a greater emphasis on knee-dominant exercises aimed at enhancing stiffness. This could help address the maturation-related lag in knee stiffness development.

Other factors involved in plyometric training effectiveness on global and intrinsic stiffness measures are training status, and program variables like frequency and volume (Ramirez-Campillo et al., 2023a). In a meta-analysis evaluating the effects of plyometric training in healthy individuals of all ages, Moran et al. (2023) reported significant small overall effect sizes ($d = 0.33$, 95% CI = 0.07, 0.6). Untrained individuals exhibited significant effect sizes ($d = 0.46$, 95% CI = 0.08, 0.84, small effect) compared to smaller non-significant effect sizes for trained individuals ($d = 0.15$, 95% CI: -0.23, 0.53, trivial effect). It is believed that untrained individuals can achieve greater improvements compared to trained participants, primarily because of their inefficient coordinative abilities. As individuals gain more experience with a specific training method, eliciting training gains becomes more challenging

(Behringer et al., 2011). However, it is unknown how more trained and active girls compared to untrained less active girls elicit stiffness adaptations. Moreover, it is unknown how maturity status and training experience interact to produce stiffness adaptations in girls. Frameworks exist which provide guidance on plyometric intensity based on expected eccentric loading (Lloyd et al., 2011c). However, in real time training, these thresholds may not be met while youth learn to properly perform plyometric exercises. Further plyometric intervention research is required where kinetic factors (e.g., vertical ground reaction force) and spatio-temporal factors (e.g., contact time) are assessed during training to ascertain their influence on training adaptations. This may reinforce the importance of choosing to administer plyometric interventions composed mostly of fast-SSC based exercises (Lloyd et al., 2011c, Lloyd et al., 2012c).

Moran et al. (2023) also discovered that interventions lasting over seven weeks consisting of 16 sessions or fewer total, had significant effect sizes. They also reported that two sessions or fewer per week and under 250 jumps per week, also had larger effect sizes. Interestingly, Lloyd et al. (2012c) administered a four-week plyometric training program for 9, 12, and 15-year-old boys, recorded as pre-PHV for the 9- and 12-year-old groups and post-PHV for the 15-year-old group. They revealed that both the 12 and 15-year-old groups improved their absolute and relative leg stiffness values significantly whereas the nine-year-old group and control group did not. These results suggest that boys can undergo leg stiffness adaptations within a brief period. If this holds true, it is likely that neural mechanisms play a significant role, such as enhanced muscle activation prior to ground contact and improved utilization of the stretch-reflex (Lazaridis et al., 2010, Dotan et al., 2012, Carrasco-López et al., 2019, Radnor et al., 2017, Turner and Jeffreys, 2010, Flanagan and Comyns, 2008). Additionally, it is probable that four weeks is insufficient to induce changes in structural factors like tendon cross-sectional area (Moran et al., 2023). Lloyd's findings (2012c) also indicate that age and maturation play a role in the outcomes of stiffness training. Additionally, the effects of such training are not solely due to increases in body size (e.g., body mass), highlighting the significance of neural-related stiffness enhancements. Therefore, further studies are required which examine differences between program parameters like training volume and how they affect stiffness development in girls. Future research may also investigate the various structural and neuromuscular adaptations to observe how these mechanisms are involved in

training-related improvements in stiffness between children and adolescents. This could provide valuable insights into how plyometric training programs can be tailored for different age groups and maturation stages to optimize performance and injury prevention.

2.4.4 Combined training

Combined training involves combinations of muscular endurance, muscular strength, power, plyometrics, speed, movement competency, and stabilization training (De Ste Croix et al., 2018, Moeskops et al., 2022a, Moeskops et al., 2018a). Combined training methods address both the neuromuscular system's capacity to generate force and attain high movement velocity. Three studies have investigated the impact of combined training on stiffness in girls only (Moeskops et al., 2022a, Moeskops et al., 2018a, De Ste Croix et al., 2018). For example, Moeskops et al. (2018a) administered a combined 8-week plyometric, strength, endurance, movement competency and dynamic stabilization training program (Neuromuscular training) in 8-year-old girls. Findings showed a significantly higher number of positive responders in the experimental group compared to a control group (41% versus 12%). The authors concluded that to achieve average stiffness adaptations across the entire group, a higher intensity of training over a longer duration was necessary.

Regarding adolescent girls, De Ste Croix et al. (2018) evaluated the effects of a 16-week combined strength, plyometric, speed, change of direction and flexibility program in 12–13-year-old girls. They demonstrated likely worthwhile improvements in relative leg stiffness measured by sub-maximal hopping (Calculated $g = 1.04$, 95% CI = 0.69, 1.39, large effect) while the control group did not (Calculated $g = 0.56$, 95% CI = 0.17, 0.94, moderate effect). The findings by De Ste Croix et al. (2018), vary from those by Moeskops et al. (2022a), who administered a 10-month intervention using combined movement competency, strength, power, and speed training (Neuromuscular training) for 9-year-old girls. Participants were grouped in a neuromuscular training combined with gymnastics training group (gNMT), a solely gymnastics training group (GYM), or a control group (CG). Relative vertical stiffness measured by drop jumping between pre-test and time two (four months), showed calculated Hedges' g effect sizes of -0.14 (95% CI = -0.84, 0.55, trivial effect), -0.24 (95% CI = -0.96,

0.48, trivial effect) and 0.17 (95% CI = -0.63, 0.98, trivial effect) in the GNMT, GYM and CG respectively. Overall, these findings may indicate the importance of considering the effect of growth and maturation on training adaptations, as well as the many variables that exist in trying to choose the most suitable combined training intervention (Ramirez-Campillo et al., 2023a). It is uncertain as to the length, training volume and exact training content that is necessary to improve stiffness in pubertal girls and beyond. It has been suggested to include exercises with shorter ground contact times, such as ankle hops, skipping, hurdle hops, and depth jumps (Turner and Jeffreys, 2010), include strength exercises that induce larger strains to affect tendon changes (Tumkur Anil Kumar et al., 2021), and train for longer than seven weeks (Moran et al., 2023). Since combined training methods can target force and movement speed adaptations, it could be suggested that combined methods are well-suited for producing stiffness adaptations. However, so far, this has not been proven in girls. Further studies are required that utilize combined methods that narrow down the required training content to elicit stiffness improvements.

2.4.5 Sprint training

Both sprinting and plyometric training involve the exertion of high rates of force development, power, and impulse against the ground (Ramirez-Campillo et al., 2023a). Moreover, they both necessitate muscle preactivation, stretch-reflex contribution, the storage and utilization of elastic energy and body projection upwards and forwards (Oliver and Smith, 2010, Clark and Weyand, 2014, Moir et al., 2018, Oliver et al., 2013). However, no researchers have used sprinting to elicit stiffness adaptations in girls. Only one study in boys has used a running training intervention (Uthoff et al., 2018). These researchers investigated the effect of running training on leg stiffness in 13–15-year-old athletic boys. They reported significant increases in leg stiffness in boys during bilateral sub-maximal hopping. It is possible that running training promoted improvements in neural factors related to the SSC such as muscle preactivation and improved stretch-reflex contribution, which help individuals rebound off the ground more effectively. Given the similarities between plyometric training and sprint training, it is worth exploring the effects of sprint training on stiffness in girls. Sprinting, like plyometric training has the advantage of being easy to

administer regardless of location or population and has been shown to be an effective and safe training method for all developmental levels (Rumpf et al., 2012).

Table 2.1. Stiffness intervention studies quantified by hopping

Author	<i>n</i>	Maturation measure	Age + SD (years)	Stiffness measure mode	Stiffness measure device	Freq (Hz)	Stiffness value + SD (kN/m)	Stiffness Measure	Value details	Intervention method; length; days/week	Volume per session (Sets x reps)	Stiffness change (Hedges' <i>g</i> + 95% CI)		
De Ste Croix et al. (2018)	71	Offset = -0.81 ± 1.16	13.1 ± 1.70	Bilateral sub-maximal hopping	Mobile contact mat	2.5	26.90 ± 4.60	Kleg, RelKleg (BM, LL)	EXP pre-test	Combined (Robustness); 16; 2	STRT: 2 x 3-30 reps, 10-60s; PT: 2 x 6-10; ST: 1-4 x 5-10-m	1.04 (0.69, 1.39)		
							34.30 ± 8.90		EXP post-test					
	54	Offset -1.01 ± 1.11	12.8 ± 1.60				25.70 ± 4.90		CG pre-test			0.56 (0.17, 0.94)		
							29.40 ± 7.90		CG post-test					
Moeskops et al. (2018)	17	pre-PHV	8.2 ± 1.70	Bilateral sub-maximal hopping	Mobile contact mat	2.5	20.20 ± 4.60	Kleg	EXP pre-test	Combined (NMT); 8; 2	2-4 x 5-10	0.12 (-0.55, 0.8)		
							20.80 ± 4.80		EXP post-test					
	17	10 ± 1.20					23.90 ± 4.80	Kleg	CG pre-test			-0.9 (-1.6, -0.19)		
Ince (2019)	17	N/R	15.63 ± 1.30	Maximal hopping	Optojump	Self-select	19.50 ± 4.80	Kleg	CG post-test	STRT (Olympic lifting); 6; 2	2-5 x 5	0.88 (0.17, 1.58)		
							35.40 ± 9.50		EXP pre-test					
	17						44.40 ± 10.50		EXP post-test			-0.06 (-0.73, 0.61)		
							35.43 ± 4.72		CG pre-test					
						35.09 ± 6.64		CG post-test						
Sylvester et al. (2024)	23	Offset = 1.7 ± 0.8	13.8 ± 1.20	Bilateral and Unilateral sub-maximal hopping	Mobile contact mat	2.0	19.40 ± 4.00	Kleg	Pre-test	Horizontal PT; 8; 2	3-6 x 10-25 m (6.2 km total)		0.44 (-0.15, 1.02)	
						2.0	21.40 ± 4.90		Post-test					
						2.2	23.20 ± 4.40		Pre-test					0.36 (-0.22, 0.95)
						2.2	24.90 ± 4.80		Post-test					
						2.5Rt	19.00 ± 2.40		Pre-test					0.19 (-0.39, 0.77)
						2.5Rt	19.50 ± 2.70		Post-test					
						2.5Lt	18.90 ± 2.70		Pre-test					0.28 (-0.31, 0.86)
						2.5Lt	19.70 ± 3.00		Post-test					
						3.0Rt	23.70 ± 4.00		Pre-test					0.38 (-0.2, 0.97)
						3.0Rt	25.40 ± 4.70		Post-test					
						3.0Lt	24.10 ± 3.40		Pre-test					0.21 (-0.37, 0.79)
3.0Lt	24.90 ± 4.00	Post-test												

n = number of participants; SD = standard deviation; Hz = Hertz; reps = repetitions; Kvert = vertical stiffness; Kleg = Absolute leg stiffness; RelKleg = relative leg stiffness; kN/m = kilonewtons per meter; NMT = neuromuscular training; EXP = experimental group; CG = control group; BM = body mass; LL = leg length; BW = body weight; CI = confidence interval; N/R = not reported; Rt = right leg; Lt = left leg; STRT = strength training; PT = plyometric training; ST = Sprint training; STRT = strength training. Note: Effect sizes calculated as Hedges' *g* using a customized spreadsheet (Cambridge, 2024).

Table 2.2. Stiffness intervention studies quantified by drop jumping

Author	<i>n</i>	Maturation measure	Age + SD (years)	Stiffness measure mode	Stiffness measure device	Freq (Hz)	Stiffness value + SD (kN/m)	Stiffness Measure	Value details	Intervention method; length; days/week	Volume per session (Sets x reps)	Stiffness change (Hedges' <i>g</i> + 95% CI)		
Moeskops et al. (2022)	16	PAH% = 75.47 ± 6.59	9.4 ± 1.8	Drop jump (30 cm)	Force plate (1000 Hz)	N/A	17.84 ± 8.55	Relative Kvert (BW/m)	gNMT-T1	Combined; 10 months; 2 days/week	3 to 5 x 3 to 8	N/A		
							16.57 ± 8.57		gNMT-T2			-0.14 (-0.84, 0.55)		
							18.72 ± 7.45		gNMT-T3			0.11 (-0.59, 0.8)		
							16.59 ± 6.63		gNMT-T4			-0.16 (-0.85, 0.53)		
	15	PAH% = 77.02 ± 6.66	9.9 ± 1.8	Drop jump (30 cm)	Force plate (1000 Hz)	N/A	19.83 ± 11.61	Relative Kvert (BW/m)	GYM-T1	Combined; 10 months; 2 days/week	3 to 5 x 3 to 8	N/A		
							17.53 ± 6.33		GYM-T2			-0.24 (-0.96, 0.48)		
							17.88 ± 9.46		GYM-T3			-0.18 (-0.9, 0.54)		
							18.87 ± 6.08		GYM-T4			-0.1 (-0.82, 0.62)		
							14.02 ± 4.9		CG-T1			N/A		
							14.81 ± 3.76		CG-T2			0.17 (-0.63, 0.98)		
12	PAH% = 73.58 ± 5.96	8.7 ± 1.6	Drop jump (30 cm)	Force plate (1000 Hz)	N/A	15.34 ± 4.49	Relative Kvert (BW/m)	CG-T3	Plyometric; 10 weeks; 2 days per week	60 to 140 contacts	0.27 (-0.53, 1.08)			
						15.34 ± 4.49		CG-T4			0.27 (-0.53, 1.08)			
						0.18 ± 0.11; 0.17 ± 0.05; 0.13 ± 0.07		EXP pre-test			-0.34 (-1.14, 0.47); -0.97 (-1.81, -0.12);			
						0.15 ± 0.05; 0.12 ± 0.05; 0.1 ± 0.04		EXP post-test			-0.51 (-1.32, 0.3)			
Katskari et al. (2020)	12	Tanner = 1-2 (Pre and Early pub)	9 to 11	Drop jump (20, 35, 50 cm)	Force plate, Motion capture	N/A	K = DJ at 20,35,50 cm	Knee stiffness	CG pre-test	Plyometric; 10 weeks; 2 days per week	60 to 140 contacts	0.25 ± 0.12; 0.2 ± 0.09; 0.14 ± 0.08		
												0.26 ± 0.12; 0.19 ± 0.08; 0.14 ± 0.09	CG post-test	0.08 (-0.72, 0.88); -0.11 (-0.91, 0.69); 0 (-0.8, 0.8)

n = number of participants; SD = standard deviation; Hz = Hertz; reps = repetitions; K = stiffness; Kvert = vertical stiffness; Kleg = leg stiffness; kN/m = kilonewtons per meter; NMT = neuromuscular training; EXP = experimental group; CG = control group; CI = confidence interval; gNMT = gymnastics + neuromuscular training group; GYM = gymnastics training group N/A = not applicable; vs = versus; T1 = pre-test; T2 = 4 months; T3 = 7 months; T4 = 10 months. Note: Effect sizes calculated as Hedges' *g* using a customized spreadsheet (Cambridge, 2024).

2.5 CONCLUSION

During the ground contact phase of fast-SSC tasks, higher amounts of stiffness allow large forces to be attenuated using a relatively smaller level of deformation of the center of mass, leg, joint, muscles, or tendon. When the force to deformation ratio is high, force application is said to be spring like, which is a characteristic that is mediated by stiffness. Moreover, the ability of stiffness to mediate spring-like force application develops naturally throughout childhood and adolescence. Absolute leg stiffness experiences a non-linear increase throughout childhood and adolescence, whereas relative leg stiffness increases linearly throughout childhood then plateaus thereafter. However, the natural development of stiffness has been attributed to different mechanisms during childhood compared to adolescence. Changes in tendon material properties and neuromuscular factors primarily explain changes during childhood, whereas changes in the tissue dimensional properties primarily explain changes during adolescence. Dimensional changes may result from mechanical loading due to growth and maturation-related increases in body mass, muscle strength or activity related loading. Notably, these findings do not imply changes during childhood or adolescence are due exclusively to one factor or the other. Nevertheless, these factors act to regulate stiffness development throughout childhood and adolescence. The training-related development of stiffness has produced significant changes through strength training, plyometric training, and combined training methods. Yet there is still uncertainty regarding whether all methods are effective for girls at all maturity stages.

CHAPTER 3. RELIABILITY OF LEG STIFFNESS DURING VERTICAL SUB-MAXIMAL HOPPING IN YOUNG FEMALE ATHLETES

3.0 PRELUDE

Chapter 2 provided a review of the literature on the development of leg stiffness during childhood and adolescence. Absolute leg stiffness exhibits a non-linear increase during these periods of time, while relative leg stiffness shows a linear rise in childhood followed by a plateau during adolescence. In children, leg stiffness development is primarily driven by changes in the intrinsic material properties of tendons (such as Young's modulus) and enhancements in neural regulation (e.g., muscle preactivation). In adolescents, however, changes in tendon dimensions, such as cross-sectional area, are more influential. Although combined training has proven effective at improving leg stiffness in adolescent girls, its impact in children is unclear. Similarly, the impact of plyometric training on leg stiffness is unclear, while the effect of linear sprint training on leg stiffness in girls is unknown. A critical aspect of training adaptations in youth is distinguishing between improvements due to training and those due to natural growth and maturation. Assessing the within-subject error through inter-session reliability analysis can help determine the degree of training-related adaptation necessary to be considered clinically significant. Clinically significant changes represent improvements beyond natural physical development. However, there is a lack of reliability data concerning leg stiffness in girls during sub-maximal hopping at various frequencies, unilateral sub-maximal hopping, and for different leg stiffness calculation methods. Chapter 3 addresses this knowledge gap by conducting a reliability analysis of leg stiffness during sub-maximal hopping; to provide the needed data so practitioners can more accurately interpret training-related adaptations in leg stiffness.

3.1 INTRODUCTION

Leg stiffness is a mechanical quality that helps manage the interaction of an externally applied force and the amount of compression that occurs in the legs (Butler et al., 2003, Brughelli and Cronin, 2008a). During the initial portion of ground contact during fast stretch-

shortening cycle (SSC) movements like sprinting and reactive jumping, a “stiff” system allows a high amount of force to be resisted by the leg over a short range of motion (Meyers et al., 2016, Millett et al., 2016). This quality increases with frequency during hopping tasks. However, at slower frequencies, spring-like behavior diminishes because the peak ground reaction force does not coincide with maximum leg compression (Moeskops et al., 2020). The augmentation of leg stiffness with hopping frequency and departure from spring-like behavior at slower sub-maximal hopping frequencies have only been observed in 16-year-old girls (Lloyd et al., 2009), while during maximal hopping, these phenomena were observed in 11–19-year-old girls (Laffaye et al., 2016). Therefore, sub-maximal hopping investigations across frequencies in girls are warranted.

Bilateral and unilateral sub-maximal hopping are likely the most suitable field-based leg stiffness measurement tasks (Maloney and Fletcher, 2018). Furthermore, different technologies have been used to measure leg stiffness in girls. These technologies include force plates (Waxman et al., 2018), tri-axial accelerometers (Myotest, Myotest S.A., Switzerland) (Laffaye et al., 2016), motion capture (Taylor et al., 2017) and floor-level optical measurement devices (İnce, 2019), all of which can provide kinetic and/or kinematic data for determining leg stiffness (Brughelli and Cronin, 2008b). However, these technologies can be costly and time consuming, making them unsuitable for many practitioners. Therefore, researchers have used more practical devices like mobile contact mats to quantify leg stiffness (Lloyd et al., 2009, Moeskops et al., 2018a, De Ste Croix et al., 2018).

Researchers have established the validity ($r > 0.9$, typical error of the estimate = 6.5-7.5%) and inter-day reliability (CV = 8.2-10.17%, ICC = 0.71- 0.92) of measuring leg stiffness while hopping bilaterally at 2.5 Hz on a contact mat in boys (Lloyd et al., 2009) and girls (De Ste Croix et al., 2017). However, researchers have not compared the accuracy and reliability of calculation methods like averaging all available contacts, all contacts within 5% of average contact time and 10 appropriate hops, when evaluating leg stiffness on a mobile contact mat during sub-maximal hopping in girls. The calculation method can affect the reliability of rebound tasks in girls (Moresi, 2011). Given that performance variability is higher in younger

girls, it is possible that calculation methods with overly stringent exclusion criteria may affect hopping reliability (Beerse and Wu, 2017). Discovering the most reliable calculation method will aid the accuracy of detecting performance changes that exceed growth and maturation related changes throughout childhood and adolescence (Lloyd and Oliver, 2023).

When examining the existing literature, it appears that no researchers have measured leg stiffness during unilateral sub-maximal hopping, using a mobile contact mat (Eiling et al., 2007, Beerse and Wu, 2016, Waxman et al., 2018). Given the unilateral nature of some sporting actions (e.g., sprinting) and the benefit of appropriate leg stiffness measures to support these actions, unilateral testing is warranted. The reliability of leg stiffness measured during bilateral or unilateral sub-maximal hopping at different hopping frequencies remains unknown in girls under 12-years-old. Instead, most researchers that conducted measurement error studies have reported in males and/or adolescent female populations. Therefore, the primary aims of this study were to (i) examine the reliability of absolute and relative leg stiffness during bilateral and unilateral sub-maximal hopping at different frequencies in girls, using a mobile contact mat, and (ii) quantify the reliability of three different calculation methods used to evaluate the consistency of sub-maximal hopping, notably, *all contacts* (AC), *all contacts* within 5% of average contact time (AC5) and 10 ‘appropriate’ hops (10Hop). The primary hypothesis was that all hopping conditions would be reliable however, there would be greater variability at a hopping frequency of 2.0 Hz compared to 2.5 Hz. The secondary hypothesis was that the AC calculation method would be the least reliable of the three calculation methods.

3.2 METHODS

3.2.1 Participants

Thirty-three female athletes between age 7-15 years from local sports clubs volunteered to participate in this study. Twenty-one participants who did not complete the third session were excluded from analysis, leaving 12 participants for the final analysis. This reflects the sample sizes of previous stiffness reliability studies in girls (Moresi, 2011, De Ste Croix et al., 2017). Participant characteristics were age, 11.35 ± 2.58 (years); standing height, 145 ± 13.52 (cm); body mass, 38.89 ± 12.09 (kg); predicted adult height percentage, 85.99 ± 8.91 (%). All participants played or trained for a sport involving impact from running or jumping and were free from injury. The average weekly sport participation based on self-reporting, was 8.24 hours. Leg dominance was determined by the stance leg during kicking (Waxman et al., 2018). By this criterion, the left leg was the dominant leg for all but one participant. All participants and parents/guardians were informed of the benefits and risks of being a part of this study. Written parental consent and participant assent were obtained prior to commencing all testing. All data collection procedures were reviewed and approved by the Institutional Research Ethics Committee (reference code: 19/434) and the study was conducted in accordance with the declaration of Helsinki.

3.2.2 Study procedures

Anthropometric data were recorded, and participants were familiarized with the testing procedures during the first familiarization session. The three subsequent testing sessions were conducted at the same time of day and on the same indoor surfaces, seven days apart. Each session began with a standardized warm-up, which included fundamental movement skills, dynamic stretching, sub-maximal hopping, a series of horizontal jumps of progressive intensity and three sprints of progressive intensity from 60% to 100% of maximal effort. Thereafter, participants performed a series of bilateral and unilateral sub-maximal hopping tests. Each participant performed each of the following bilateral hopping tests at frequencies of 2.0 Hz and 2.2 Hz, as well as unilateral hopping frequencies (dominant and non-dominant leg), at 2.5 Hz and 3.0 Hz. Consistent verbal encouragement was used across all tests.

Participants were asked to refrain from vigorous physical activity 24 hours prior to each session.

3.2.3 Testing protocols

3.2.3.1 Anthropometric and maturity measures

Participant standing height and seated height were measured using a stadiometer (Seca 213, Portable Stadiometer), using the method outlined by Simmons (2000). Leg length was determined by subtracting seated height from standing height. Body mass was measured using a Bioelectric Impedance Analysis device (Tanita® Sc-240, Tanita Corporation, Tokyo, Japan). The anthropometric variables, along with age and the average stature of both biological parents were used to estimate maturity status based on the percentage of predicted adult height method (Khamis and Roche, 1994). Calculations were completed using a customised Microsoft Excel® 2015 worksheet (Towlson et al., 2020).

3.2.3.2 Hopping procedures

Vertical bilateral and unilateral sub-maximal hopping were performed on a contact mat (Smartjump; Fusion Sport, Brisbane, Australia). Following familiarization, one trial of 20 consecutive hops was completed while attempting to match a range of cued frequencies from 2.0 Hz to 3.0 Hz set on a digital metronome (Lloyd et al., 2009). To minimize interference from the arms and trunk, participants were instructed to keep their hands on hips, jump and land on the same spot, land with legs extended and maintain their gaze forwards (Lloyd et al., 2009). To help mitigate the effects of fatigue, three-minutes of passive rest were given between each trial. Data were collected instantaneously through the contact mat and attached electronic hub (Smartjump; Fusion Sport, Brisbane, Australia) and exported to the online cloud-based data storage system (Smart-jump, Fusion Sport, Brisbane, Australia).

3.2.3.3 Data analyses

The calculation methods used involved determining the between-session reliability of stiffness from 1) all contacts (AC), 2) all contacts within 5% of average contact time (AC5),

and 3) 10 consecutive “appropriate” hops (Moresi et al., 2015). To determine the “appropriate” hops, the first four hops and last 6 hops were removed, leaving the 10 remaining “appropriate” hops. For the AC5 method, a pivot table in Microsoft Excel® 2015 was generated from which calculations were made. Clearly erroneous or atypical hops in which the participant paused too long on the mat or did not fully contact the mat were excluded. Those contacts generally exceeded 300 ms of contact time. All relative stiffness conditions were analyzed using the most reliable calculation method. Absolute leg stiffness (kN/m) was calculated from contact time and flight time data automatically by the contact mat software, which used the sine wave method outlined in Dalleau et al. (2004), Equation 1, where M = body mass (kg), π = the half period of the sine wave, T_f = flight time (s), T_c = contact time (s), K_{vert} = vertical stiffness (kN/m)

$$K_{leg} = [M * \pi (T_f + T_c)] / T_c^2 [(T_f + T_c / \pi) - (T_c / 4)]$$

[Equation 1]

Relative leg stiffness was also calculated in three separate ways. The first by dividing absolute leg stiffness by body mass (Waxman et al., 2018) [Equation 2], the second by dividing absolute leg stiffness by leg length (De Ste Croix et al., 2018) [Equation 3] and the third by multiplying absolute leg stiffness by the quotient of leg length and body mass to provide a dimensionless value (Lloyd et al., 2009, De Ste Croix et al., 2017) [Equation 4].

$$\frac{K_{leg}}{M} = \text{Leg stiffness relative to body mass (kg)}$$

[Equation 2]

$$\frac{K_{leg}}{LL} = \text{Leg stiffness relative to leg length (cm)}$$

[Equation 3]

$$K_{leg} \times \left[\frac{LL}{M} \right] = \text{Leg stiffness relative to leg length and body mass}$$

[Equation 4]

3.3 STATISTICAL ANALYSES

The descriptive statistics (mean +/- SD) for sub-maximal hopping were evaluated for normality by inspecting *Z* scores for skewness and kurtosis, extreme outliers in the interquartile (box and whiskers) plot, and examination of a Shapiro-Wilk test (Cain et al., 2017, Statology, 2022, Ghasemi and Zahediasl, 2012). Furthermore, homogeneity of variance of the differences was evaluated using a Mauchly's test of Sphericity (Blanca et al., 2023). Inter-session reliability for all performance tests was determined through several statistical procedures in SPSS 28 (version 28; SPSS Inc, Chicago, IL). *Firstly*, a repeated measures analysis of variance (RMANOVA) of within-subject effects using a Bonferroni post hoc analysis was used to examine whether there was a systematic difference between the test sessions (Atkinson and Nevill, 1998). *Secondly*, average CV% with 95% confidence intervals (CI) were used to determine absolute reliability. Values for CV of $\leq 10\%$ were considered to possess acceptable reliability (Maloney et al., 2015). *Thirdly*, a two-way, mixed effects, single rater, intraclass correlation coefficient (ICC) using absolute agreement with 95% confidence intervals (CI 95%), was used to determine relative reliability (Atkinson and Nevill, 1998, Koo and Li, 2016). ICC values above 0.9, between 0.75-0.90, between 0.5 and 0.75 and below 0.5 were considered excellent, good, moderate, and poor, respectively (Koo and Li, 2016). Additionally, the presence of an ICC lower bound 95% confidence interval of 0.8 or above (Diggin et al., 2016) was considered as acceptable reliability.

To determine sample size, a power analysis was performed using G*Power version 3.1.9.7 (Faul et al., 2007). The parameters were entered as follows, effect size 0.1-0.15, statistical significance, $\alpha = 0.05$, power, $1-\beta = 0.80$, number of groups, one, correlation, 0.9, non-sphericity correction, 0.75 (Lloyd et al., 2009, Faul et al., 2007). According to these parameters, the required sample size was between 12 and 20 participants. With 12 participants, this requirement was satisfied.

3.4 RESULTS

The mean, SD, change in mean, average CV% and ICC for all between session data, including six hop conditions and three calculation methods are summarized in Table 3.1. Statistically significant ($p < 0.05$) differences were observed for the AC5 and 10Hop conditions at 2.5 Hz on the non-dominant leg between testing occasions one and three. While there were significant overall effects for leg stiffness relative to body mass and leg stiffness relative to leg length, no significant pairwise differences were noted for any relative stiffness condition which were all calculated using the AC method.

All hopping tests were found to have average CV values $< 10\%$, indicating acceptable absolute reliability. Notably, dominant leg hopping at 2.5 Hz had the lowest average CV% (3.89%), whereas hopping at 2.0 Hz had the highest (9.44%). Relative consistency between sessions were on average ICC > 0.9 for all absolute and relative hopping conditions, indicating excellent agreement. Furthermore, only one hop condition (2.0 Hz, ICC lower CI = 0.76) had a lower bound CI below 0.8 (2.0 Hz, 10Hop). All calculation methods were deemed reliable; however, the AC method was the most consistent. Notably, the AC method showed no significant pairwise differences, minimal change in mean (0.15 to 0.81 kN/m), yielded the lowest average CV% in four of six hop conditions (2.0 Hz, 8.23 %, 2.2 Hz, 7.25%, 2.5 HzD, 3.89%, 3.0 HzND, 5.48%), excellent average ICC (0.94 to 0.99), and lower bound CI exceeding 0.8 for all hop conditions.

Table 3.1. Absolute leg stiffness reliability

Variable	CM	Means with SD (kN/m)			Raw change in mean with Lower + Upper CI (95%)			CV (%) + 95% CI Mean (%)	ICC with Lower + Upper CI (95%) Mean
		Day 1	Day 2	Day 3	1 to 2	2 to 3	1 to 3		
2.0 Hz	AC	15.70 ± 3.12	15.36 ± 3.47	16.37 ± 4.35	-0.34 (-1.41 to 0.73)	1.01 (-0.74 to 2.75)	0.67 (-1.30 to 2.64)	8.23 (6.27 to 10.19)	0.94 (0.85 to 0.98)
2.0 Hz	AC5	15.49 ± 3.12	14.97 ± 3.29	15.97 ± 4.39	-0.53 (-1.58 to 0.53)	1.00 (-0.71 to 2.71)	0.48 (-1.60 to 2.55)	8.26 (5.98 to 10.54)	0.94 (0.84 to 0.98)
2.0 Hz	10Hop	15.63 ± 3.02	15.25 ± 3.31	16.23 ± 4.76	-0.38 (-1.43 to 0.66)	0.98 (-1.49 to 3.46)	0.60 (-1.90 to 3.10)	9.44 (5.88 to 13.01)	0.91 (0.76 to 0.97)
2.2 Hz	AC	17.39 ± 3.32	17.36 ± 4.55	18.20 ± 4.42	-0.03 (-1.70 to 1.64)	0.84 (-1.20 to 2.88)	0.81 (-1.13 to 2.75)	7.25 (3.70 to 10.81)	0.95 (0.86 to 0.99)
2.2 Hz	AC5	16.93 ± 3.33	17.05 ± 4.62	17.87 ± 4.45	0.13 (-1.59 to 1.85)	0.82 (-1.24 to 2.87)	0.95 (-0.95 to 2.84)	8.04 (4.83 to 11.26)	0.95 (0.86 to 0.99)
2.2 Hz	10Hop	16.75 ± 3.35	17.21 ± 4.48	18.23 ± 5.01	0.46 (-1.21 to 2.13)	1.02 (-1.19 to 3.23)	1.48 (-1.37 to 4.33)	9.29 (5.35 to 13.22)	0.92 (0.80 to 0.98)
2.5 HzND*	AC	13.44 ± 2.18	13.85 ± 2.47	14.21 ± 2.83	0.42 (-0.24 to 1.08)	0.36 (-0.42 to 1.13)	0.77 (-0.04 to 1.58)	4.35 (2.91 to 5.78)	0.97 (0.92 to 0.99)
2.5 HzND*	AC5	13.28 ± 2.33	13.70 ± 2.62	14.03 ± 2.71	0.42 (-0.32 to 1.16)	0.33 (-0.36 to 1.02)	0.75 # (0.02 to 1.47)	4.30 (2.62 to 5.98)	0.98 (0.93 to 0.99)
2.5 HzND *	10Hop	13.35 ± 2.23	13.85 ± 2.36	14.37 ± 2.97	0.51 (-0.11 to 1.13)	0.52 (-0.36 to 1.40)	1.03 # (0.10 to 1.95)	4.75 (3.04 to 6.46)	0.96 (0.88 to 0.99)
2.5 HzD	AC	13.59 ± 2.83	13.81 ± 2.96	13.74 ± 2.88	0.22 (-0.47 to 0.90)	-0.07 (-0.73 to 0.58)	0.15 (-0.57 to 0.86)	3.89 (2.75 to 5.04)	0.99 (0.97 to 1.00)
2.5 HzD	AC5	13.28 ± 2.81	13.59 ± 2.92	13.67 ± 2.95	0.31 (-0.28 to 0.89)	0.08 (-0.70 to 0.86)	0.39 (-0.45 to 1.23)	4.41 (3.05 to 5.76)	0.98 (0.96 to 1.00)
2.5 HzD	10Hop	13.35 ± 2.79	13.67 ± 2.74	13.59 ± 2.87	0.33 (-0.61 to 1.26)	-0.08 (-0.69 to 0.53)	0.25 (-0.84 to 1.33)	4.82 (2.86 to 6.79)	0.98 (0.94 to 0.99)
3.0 HzND	AC	18.03 ± 4.27	17.97 ± 3.79	18.53 ± 4.15	-0.01 (-1.61 to 1.50)	0.56 (-0.83 to 1.94)	0.50 (-0.53 to 1.53)	5.48 (3.48 to 7.48)	0.98 (0.93 to 0.99)
3.0 HzND	AC5	17.82 ± 4.31	17.85 ± 3.96	18.55 ± 4.12	0.03 (-1.40 to 1.45)	0.71 (-0.72 to 2.13)	0.74 (-0.26 to 1.73)	5.84 (4.02 to 7.66)	0.98 (0.93 to 0.99)
3.0 HzND	10Hop	18.15 ± 4.21	18.08 ± 3.85	18.52 ± 4.4	-0.06 (-1.85 to 1.73)	0.44 (-0.89 to 1.76)	0.37 (-0.67 to 1.42)	5.79 (3.72 to 7.86)	0.97 (0.93 to 0.99)
3.0 HzD	AC	18.68 ± 4.78	18.64 ± 5.03	19.15 ± 4.19	-0.03 (-1.05 to 0.98)	0.51 (-0.97 to 1.99)	0.48 (-0.85 to 1.80)	5.13 (3.20 to 7.05)	0.98 (0.95 to 0.99)
3.0 HzD	AC5	18.48 ± 4.66	18.54 ± 4.97	18.83 ± 4.16	0.07 (-0.82 to 0.95)	0.29 (-1.05 to 1.63)	0.36 (-0.80 to 1.52)	4.48 (2.77 to 6.19)	0.99 (0.96 to 1.00)
3.0 HzD	10Hop	18.46 ± 4.84	18.53 ± 5.14	19.33 ± 4.11	0.08 (-0.82 to 0.97)	0.80 (-1.29 to 2.89)	0.88 (-1.10 to 2.85)	7.19 (3.95 to 10.43)	0.96 (0.90 to 0.99)

HZ = Hertz; HzND = Non-dominant; HzD = Dominant; AC = All contacts; AC5 = all contacts within 5% of average contact time; 10Hop = 10 appropriate hops

*Indicates a within subject effect (significant F); # indicates a significant pairwise difference; CM = calculation method.

3.5 DISCUSSION

This was the first study to involve a comprehensive statistical approach to quantify the reliability of bilateral and unilateral sub-maximal hopping on a mobile contact mat across multiple hopping frequencies in young girls. The main findings were that the absolute and relative leg stiffness values across all hopping conditions and calculation methods, except for one condition (non-dominant leg, 2.5 Hz) were found to have acceptable absolute and relative reliability and no systematic differences between paired sessions. Dominant leg hopping at 2.5 Hz and the AC method were identified as the most suitable hopping condition and calculation method, respectively. Although there were no other differences of note while comparing all the relative leg stiffness conditions, leg stiffness relative to body mass and leg length (RelBM/LL) is still recommended as the most biologically relevant normalization method.

3.5.1 Change in mean

The change in the mean was calculated to determine if there was systematic change between testing occasions, indicating learning, order, motivation, or fatigue effects (Atkinson and Nevill, 1998, Hopkins, 2000). Irrespective of hopping condition or calculation method, the change in mean between sessions was typically random and small. Although the slower bilateral hops generally showed a greater change in the mean and broader confidence intervals, all change in mean values ranged from -0.53 to 1.48 kN/m for absolute leg stiffness and -0.84 to 2.13 among relative leg stiffness measures, which are lower than the relative leg stiffness values of De Ste Croix et al. (2017) (-2.23 to 4.48) but higher than Moresi (2011) (-0.57 to 0.29). The differences between studies could be attributed to methodological variations, such as task type, hopping frequency, and the number of sessions. However, the significant change in the mean between sessions one and three for hopping at 2.5 Hz on the non-dominant leg may be explained by the underlying mechanisms of hopping. For example, of the three testing sessions, the best contact time occurred on session three, specifically, 212.8 ms, compared to 222.17 ms and 218.4 ms in sessions one and two respectively. Furthermore, the actual frequency achieved by the participants remained within the 2.5 Hz framework, specifically those frequencies were 2.50 Hz, 2.54 Hz and 2.52 Hz during session

one, two, and three respectively. These findings may suggest that by the third session, a higher hopping height was achieved on the non-dominant leg. Presumably the non-dominant leg does not achieve the same level of peak force, impulse, and may be less coordinated (Meylan et al., 2010, De Ste Croix et al., 2017). It is possible that these presumed deficits on the non-dominant leg was decreased by the third session or that there was a learning effect in which the control and coordination of the ground contact period was improved (Lloyd et al., 2009). Regardless, the protocols outlined in this study elicit small non-systematic changes in mean.

3.5.2 Absolute consistency

The typical error associated with testing was quantified using average CV%, which is also known as a measure of absolute consistency (Atkinson and Nevill, 1998, Hopkins, 2000). Irrespective of hopping condition or calculation method, average CV percentages were less than 10%, indicating acceptable reliability (Atkinson and Nevill, 1998). These findings agree with De Ste Croix et al. (2017), who reported an average CV% of 8.2% to 9.7% for 12-17-year-old girls for relative leg stiffness. Similarly, Lloyd et al. (2009) demonstrated better absolute consistency for sub-maximal hopping at 2.5 Hz compared to 2.0 Hz in 13.5 year-old boys. Sub-maximal hopping at 2.0 Hz may be less spring-like compared to sub-maximal hopping 2.5 Hz due to a lower force to displacement ratio (Lloyd et al., 2009). This diminished spring-like behavior during sub-maximal hopping at 2.0 Hz may be comparable to maximal hopping, which has shown CVs of 10.7% to 14.5% (Moresi, 2011). Therefore, SSC tasks used to quantify leg stiffness that are more spring-like are more reliable.

3.5.3 Agreement between sessions

Agreement between sessions was quantified using the ICC. Irrespective of leg stiffness measure or calculation method, all ICCs were greater than 0.90, indicating excellent agreement over repeated testing occasions (Koo and Li, 2016). De Ste Croix et al. (2017) reported ICC values of 0.71 to 0.91 for relative leg stiffness in 12-17-year-old girls, while Moresi (2011) reported ICC values of 0.62 to 0.77. It would be expected that the ICC values in this study would be lower given that the girls of this study were younger and less mature

compared to those of De Ste Croix et al. (2017) and Moresi (2011). However, this was not the case. It is possible that that the girls in this study: 1) had better motor ability and experience with hopping; 2) were less fatigued compared to the participants of De Ste Croix et al. (2017); 3) were not experiencing the same rapid growth in body size compared to the girls of De Ste Croix et al. (2017) and Moresi (2011).

3.5.4 Reliability of calculation methods

The secondary aim of this study was to evaluate the reliability of three different calculation methods to assess sub-maximal hopping tasks. Contrary to the secondary hypothesis, the AC method was found to have the best reliability amongst the three analytic methods for absolute and relative leg stiffness conditions. Due to the limited exclusion of hops, the AC method may have maintained the integrity of the sample of recorded hops better than the other calculation methods (Moresi et al., 2015). This method offers a simple, accurate and reliable method for the assessment of young female athletes hopping on a mobile contact mat. The AC5 method resulted in too many hops being excluded, while the 10Hop had the highest CV% for all but one hopping condition (3.0 HzND).

3.6 LIMITATIONS

It is acknowledged, the reliance on a contact mat prevents direct measurement of vertical ground reaction force which allows determination of true spring mass behavior (Maloney and Fletcher, 2018). However, the portability and cost of a contact mat, provides users with a practical option to measure stiffness qualities. Finally, due to the small sample size, future researchers may consider applying the methods from this study to a larger and more diverse sample, including participants at different stages of maturity, to better understand the reliability of leg stiffness across varying maturity levels in girls. However, the establishment of unilateral leg stiffness reliability from the current study will aid in establishing within-subject error for properly interpreting training related improvements in leg stiffness in young girls (Turner et al., 2015).

3.7 CONCLUSION AND PRACTICAL APPLICATIONS

This was the first study establishing the leg stiffness reliability of unilateral sub-maximal hopping methods in girls across different frequencies on a contact mat. The practitioner can be confident that the hopping conditions evaluated can reliably measure leg stiffness on a mobile contact mat in young girls. This reliability was present irrespective of calculation method or whether the hops were bilateral or unilateral, except for unilateral hops on the non-dominant leg at 2.5 Hz. Two familiarization sessions are recommended to mitigate learning effects. The CV values obtained in this study represent the typical error associated with leg stiffness during sub-maximal hopping in girls. This typical error may indicate the degree of training-related improvement needed to accurately interpret training-related changes as clinically meaningful (Turner et al., 2015). For example, an improvement in leg stiffness while hopping at 2.5 Hz unilaterally would need to exceed 4.35% and 3.89% on the non-dominant and dominant leg respectively to be considered a clinically meaningful change. More accurate interpretations of clinically significant training-related changes can more appropriately inform practitioners of the implications of a given training strategy.

CHAPTER 4. RELIABILITY OF HORIZONTAL JUMPING AND HOPPING IN YOUTH FEMALE ATHLETES OF DIFFERING MATURITY STATUS

4.0 PRELUDE

The findings of Chapter 3 showed sub-maximal hopping on the dominant leg at 2.5 Hz to be the most reliable condition for assessing leg stiffness in girls. Additionally, the 'all contacts' calculation method was the most reliable among the three options examined. Data from Chapter 3 also established the within-subject error for leg stiffness during sub-maximal hopping in girls, above which, training-related changes can be considered clinically significant. However, there is no such data available for many horizontal field-based tests that may help practitioners monitor explosive jumping and hopping ability in girls. Thus, Chapter 4 sought to explore the inter-session reliability of a series of horizontal hopping and jumping tests both single and repeated. These tests can present the relevant within-subject error for horizontal jumping and hopping, above which training-related changes can be considered clinically significant.

4.1 INTRODUCTION

Horizontal jumping and hopping tests are practical, inexpensive, and minimally time-consuming tests (McCubbine et al., 2018, Myers et al., 2014) that are used to assess lower body explosive capability in young girls (Castro-Pinero et al., 2010, Fernandez-Santos et al., 2018, Milliken et al., 2008). However, many indicators of lower body explosive capability in youth are influenced by maturity-related differences in body size, composition, and limb lengths (Malina and Katzmarzyk, 2006, Moeskops et al., 2018b). For example, being taller, heavier with more fat mass may limit how well one's body can be projected into the air during jumping tasks (Malina and Katzmarzyk, 2006, Moran et al., 2018b). Furthermore, the rate and timing of maturation may also affect tasks that require high levels of motor coordination, especially during periods of accelerated growth or with periods of temporary disruption in

motor coordination (adolescent awkwardness) (Lloyd et al., 2014b, Nagano et al., 2007). Given the impact of maturation on the ability to project the body into the air, it is warranted to investigate this relationship in a variety of jumping and hopping tasks. This will allow researchers to identify the error associated with different stages of maturation to improve the accuracy of explosive testing in girls (Meylan et al., 2012, Meylan et al., 2014a).

A variety of horizontal jumping and hopping tasks have been used by researchers, including but not limited to, the broad jump (Michailidis et al., 2013, Thams et al., 2021, Moresi et al., 2011, Fang and Ho, 2020), broad hop (Bishop et al., 2018, Myers et al., 2014, Greenberg et al., 2014, McCubbine et al., 2018, Ramirez-Campillo et al., 2018), triple broad hop (McCubbine et al., 2018, Bishop et al., 2018, Steffen et al., 2013, Myers et al., 2014, Greenberg et al., 2014, Maulder and Cronin, 2005), and crossover hop (Bishop et al., 2018, McCubbine et al., 2018). Researchers have assessed the intra-day reliability of the broad jump in children age 3-6 years (Fang and Ho, 2020), whereas, Thams et al. (2021) reported the inter-day reliability of the broad jump test in girls age 6-9 years, observing a CV% of 6.8-7.9 % and ICC of 0.86-0.87. However, researchers have not assessed the reliability of the triple broad jump test in girls, and there is a scarcity of studies where researchers have assessed the inter-day reliability of broad hopping in young girls. For example, McCubbine et al. (2018) reported the inter-day reliability of broad hops (CV% = 4-4.1%, ICC = 0.72 to 0.76) and triple broad hops (CV% = 3.3 % to 3.5%, ICC = 0.85 to 0.87) in 10-year-old children. Myers et al. (2014) reported the reliability of asymmetries in adolescent girls, rather than reporting the inter-day reliability. Finally, administering a broad hopping test that is suitable for girls of varying maturity status and a wide age range can be challenging due to coordination differences (Wild et al., 2016, Masci et al., 2012). Coordination deficits, for example, during landing from a jump, may lead to initial performance deficits followed by a rapid learning effect that confounds reliability (Atkinson and Nevill, 1998, Hopkins, 2000, Wild et al., 2016). This study proposed a solution aimed at having participants complete the final landing of all hopping tests on both feet. This protocol was proposed as more suitable for individuals at all stages of maturation to reduce excessive learning effects that could potentially produce less reliable test results. Given this brief treatise of literature, the aim was to assess the reliability of a series of hops and jumps, in girls of differing maturity status

while landing all tests on two feet. The findings of this study will guide researchers and practitioners on testing methods for horizontal jumping and hopping, that may accommodate girls of different maturity status, thus enabling better diagnostics and exercise prescription.

4.2 METHODS

4.2.1 Participants

Twenty-three girls aged 7-15 years completed testing for this study. All participants played a sport involving running or jumping movements and were free from major orthopedic injuries (e.g., sprains, fractures, and tears) for at least three months prior to the start of the study. Participants were analyzed as a less mature group comprising nine pre-pubertal and early pubertal girls [Predicted adult height percentage (PAH%), $80.77 \pm 4.53\%$; Age, 9.87 ± 1.50 years; Height, 135.94 ± 7.84 cm; Body mass, 31.18 ± 6.75 kg], and a more mature group of 14 late pubertal girls (PAH% $97.74, \pm 1.43\%$; Age, 14.47 ± 0.94 years; Height, 164.46 ± 8.34 cm; Body mass, 56.27 ± 9.78 kg). The average weekly hours of sport participation, as determined by self-reporting, was 8.41 hours. All participants and parents/guardians were informed of the benefits and risks of being a part of this study. Written parental consent and written participant assent was obtained prior to data collection. All data collection procedures were reviewed and approved by the Institutional Research Ethics Committee (reference code: 19/434) and the study was conducted in accordance with the declaration of Helsinki.

4.2.2 Study procedures

Participants attended one familiarization session, during which anthropometric measurements were taken, followed by three data collection sessions (Hopkins, 2000). Testing sessions were conducted at the same time of day, and on the same indoor surface seven days apart. Each session began with a standardized warm-up, including fundamental movement skills, dynamic stretching, sub-maximal hopping, a series of horizontal jumps of progressive intensity and three sprints of progressive intensity from 60-100% of maximal effort. Verbal encouragement remained consistent for each participant across all trials and

sessions. Participants were asked to refrain from any vigorous physical activity 24 hours prior to the testing sessions.

4.2.3 Testing protocols

4.2.3.1 Anthropometric and maturity measures

Maturity status was assessed using a series of anthropometric measures to estimate predicted adult height percentage (PAH%) based on the method by Khamis and Roche (1994) and calculated using the spreadsheet by Towlson et al. (2020). In this method: PAH% < 85% was considered pre-pubertal; $\geq 85\%$ to < 90% was considered in the early pubertal stage; $\geq 90\%$ to < 95% was considered mid-pubertal; and $\geq 95\%$ was considered late pubertal (Cumming et al., 2017). Standing and seated height were measured using a stadiometer (Seca 213, Portable Stadiometer) with leg length calculated afterwards by subtracting seated height from standing height (Simmons, 2000). Body mass and body fat percentage were measured using a Bioelectric Impedance Analysis device, the Tanita® Sc-240 (Tanita Corporation, Tokyo, Japan).

4.2.3.2 General jump and hop protocols

Maximal horizontal jump and hop performance was assessed using a standard fiberglass tape measure (Mastercraft®). The distance from the starting line to the heel of the foot closest to the start line was measured after the jumps or hops were executed with the participant remaining in place until instructed otherwise by the researcher. Participants were allowed to practice all tests prior to having their attempt measured. There were no restrictions placed on arm movement or where to maintain their gaze for any of the tests. Furthermore, to add an element of safety, the hops were completed with a final landing on two feet (Reid et al., 2007). Measurements were made to the nearest 0.2 cm for each of the two trials (Silva et al., 2022) for each jump and hop condition. All jump and hop conditions were considered faults if the participant moved their foot upon their final landing, or if the participant put their hands on the ground to stabilize themselves upon the final landing (Standing and Maulder, 2019).

4.2.3.3 Specific broad jump and triple broad jump testing protocols

Participants started in a standing position with the toes of both feet behind the start line and arms raised parallel to the ground. During the single bilateral jump, participants were instructed to perform a single maximal jump for distance (cm), with use of a countermovement and completing the landing on both feet (Standing and Maulder, 2019). During the triple broad jumps, participants completed three consecutive maximal jumps for distance without pausing between jumps and landing from the last jump on two feet (Hudgins et al., 2013).

4.2.2.4 Broad hop and triple broad hop testing protocols

Participants started in a standing position with one leg in the air and the toes of their stance leg behind the start line and arms raised parallel to the ground. During the broad hop test, participants were instructed to perform a countermovement immediately followed by a maximal hop for distance (cm), completing the landing on two feet (Rivera et al., 2023, Standing and Maulder, 2019). The triple broad hop tests required participants to perform three maximal consecutive hops for distance without pausing between hops and landing from the last hop on two feet. Hops were considered a fault if the free leg touched the ground prior to the final bilateral landing (Standing and Maulder, 2019).

4.3 STATISTICAL ANALYSES

The descriptive statistics (mean +/- SD) for horizontal jumping and hopping were evaluated for normality by examining Z scores for skewness and kurtosis, extreme outliers in the interquartile (box and whiskers) plot, and examination of a Shapiro-Wilk test (Cain et al., 2017, Statology, 2022, Ghasemi and Zahediasl, 2012). Furthermore, homogeneity of variance of the differences was evaluated using a Mauchly's test of Sphericity (Blanca et al., 2023). Any violation of sphericity was corrected for by interpreting the Greenhouse-Geisser values. These evaluations revealed a normal data set for both groups. Inter-session reliability for all performance tests for the less mature group and more mature group were determined through several statistical procedures in SPSS (SPSS®, V.28. Chicago, Illinois). *Firstly*, a repeated

measures ANOVA of within-subject effects using a Bonferroni post hoc analysis was used to examine whether there was systematic bias between the test sessions (Atkinson and Nevill, 1998). *Secondly*, average CV% with 95% confidence intervals was used to determine absolute reliability. Values for CV of $\leq 10\%$ were considered acceptable reliability (Maloney et al., 2015). *Thirdly*, two-way mixed effect, single rater intraclass correlation coefficient, with 95% confidence intervals (CI) and absolute agreement was used to determine relative reliability (Atkinson and Nevill, 1998, Koo and Li, 2016). ICC values above 0.9, between 0.75-0.90, between 0.5 and 0.75 and below 0.5 were considered excellent, good, moderate, and poor respectively (Koo and Li, 2016). ICC results indicated whether there was stability in the ranking of the test results (Atkinson and Nevill, 1998). Another consideration for ICC was the presence of a lower bound 95% confidence interval of 0.8 or above (Diggin et al., 2016). Statistical significance was set at the level of $p < 0.05$.

To determine sample size, a power analysis was performed using G*Power version 3.1.9.7 (Faul et al., 2007). The parameters were entered as follows, effect size 0.1-0.2, statistical significance, $\alpha = 0.05$, power, $1-\beta = 0.80$, number of groups, two, correlation, 0.8, non-sphericity correction, 0.75 (McCubbine et al., 2018, Faul et al., 2007). According to these parameters, the required sample size was between 22 and 82 participants. With 23 participants, this requirement was satisfied.

4.4 RESULTS

The mean, SD, change in mean, average CV%, ICC between all three sessions for all jump and hop types of both groups are summarized in Tables 4.1 and 4.2. No significant pairwise (post hoc) differences were observed across testing occasions in the less mature group. Furthermore, all CVs were below 7.5%, including the triple broad hop right (TBHR) and triple broad hop left (TBHL), which had the largest CVs. The ICCs for all jump and hop tests for both maturity groups were greater than 0.92. Additionally, the lower bound confidence intervals were all above 0.8 except for the TBHL of the less mature group with a lower bound estimate of 0.78. Regarding the more mature group, significant pairwise differences between sessions 1-3 were observed for all but the BJ test (see Table 4.2). Mature group CVs were

below 3.8%, and ICCs greater than 0.94, with the greatest variability associated with the SBHL. Overall, the less mature group performed better regarding systematic differences between sessions. However, the more mature group generally had better absolute reliability, lower SD around the mean, and more narrow confidence intervals regarding the change in mean.

Table 4.1. Horizontal jump and hop reliability results for the less mature group

Less mature group	Means with SD (cm)			Raw change in mean with Lower + Upper CI (95%) (cm)			CV (%) + 95% CI	ICC with Lower + Upper CI (95%)
	Day 1	Day 2	Day 3	1 to 2	2 to 3	1 to 3	Mean (%)	Mean
BJ	147.28 ± 22.64	145.77 ± 22.64	147.54 ± 20.18	-1.52 (-9.30 to 6.27)	1.78 (-4.32 to 7.88)	0.26 (-6.67 to 7.19)	2.91 (1.21 to 4.61)	0.98 (0.95 to 1.00)
SBHR [^]	130.23 ± 23.43	133.60 ± 21.60	138.79 ± 19.03	3.38 (-4.15 to 10.90)	5.19 (-1.13 to 11.51)	8.56 (-3.53 to 20.66)	4.60 (1.83 to 7.37)	0.96 (0.86 to 0.99)
SBHL	129.26 ± 21.49	131.38 ± 20.34	137.01 ± 19.13	2.12 (-1.76 to 6.01)	5.63 (-3.48 to 14.75)	7.76 (-0.39 to 15.9)	4.01 (1.44 to 6.58)	0.97 (0.88 to 0.99)
TBJ	453.43 ± 59.48	451.67 ± 57.36	442.80 ± 59.78	-1.77 (-23.2 to 19.67)	-8.87 (-27.57 to 9.83)	-10.63 (-40.00 to 18.73)	3.13 (0.95 to 5.31)	0.97 (0.92 to 0.99)
TBHR [^]	376.65 ± 105.79	385.99 ± 80.39	378.89 ± 73.53	9.34 (-40.59 to 59.27)	-7.10 (-30.8 to 16.6)	2.24 (-59.13 to 63.6)	7.01 (4.22 to 9.79)	0.96 (0.87 to 0.99)
TBHL	356.42 ± 93.52	385.46 ± 65.63	385.84 ± 54.27	29.03 (-4.55 to 62.62)	0.39 (-33.69 to 34.46)	29.42 (-24.38 to 83.22)	7.46 (0.78 to 14.13)	0.93 (0.78 to 0.98)

SD = standard deviation; CV = coefficient of variation; ICC = Intraclass correlation coefficient; CI = confidence interval; cm = centimeters; BJ = Broad jump; SBHR = Single broad hop right; SBHL = Single broad hop left; TBJ = Triple broad jump; TBHR = Triple broad hop right; TBHL = Triple broad hop left.

*Indicates a within subject effect (significant F); # indicates location of significant pairwise difference; ^ Indicates violation of sphericity.

Table 4.2. Horizontal jump and hop reliability results for the more mature group

More mature group Variable	Means with SD (cm)			Raw change in mean with Lower + Upper CI (95%) (cm)			CV (%) + 95% CI	ICC with Lower + Upper CI (95%)
	Day 1	Day 2	Day 3	1 to 2	2 to 3	1 to 3	Mean (%)	Mean
BJ	177.31 ± 17.03	176.15 ± 13.53	178.02 ± 15.40	-1.15 (-6.45 to 4.14)	1.87 (-2.65 to 6.38)	0.71 (-5.00 to 6.42)	2.82 (2.12 to 3.51)	0.95 (0.89 to 0.98)
SBHR*	162.95 ± 16.14	167.80 ± 15.62	168.52 ± 16.15	4.85 (-0.1 to 9.81)	0.72 (-3.91 to 5.35)	5.57 (1.42 to 9.73) #	3.21 (2.32 to 4.11)	0.96 (0.88 to 0.98)
SBHL*	160.35 ± 16.50	165.06 ± 16.79	167.91 ± 16.69	4.72 (-0.26 to 9.70)	2.85 (-2.61 to 8.30)	7.57 (2.14 to 12.99) #	3.75 (2.77 to 4.72)	0.94 (0.84 to 0.98)
TBJ*	523.78 ± 51.75	537.02 ± 45.02	539.92 ± 51.33	13.24 (-2.72 to 29.20)	2.90 (-9.02 to 14.81)	16.14 (-2.05 to 34.33)	2.98 (1.85 to 4.10)	0.95 (0.88 to 0.98)
TBHR*	489.15 ± 53.59	504.18 ± 62.98	503.49 ± 59.74	15.02 (-2.37 to 32.42)	-0.69 (-18.49 to 17.11)	14.34 (0.93 to 27.74) #	3.32 (2.15 to 4.48)	0.97 (0.92 to 0.99)
TBHL*	481.19 ± 53.59	504.18 ± 53.58	497.29 ± 55.04	12.54 (-3.25 to 28.33)	-6.89 (-14.15 to 21.27)	16.1 (4.11 to 28.09) #	3.15 (2.24 to 4.06)	0.96 (0.90 to 0.98)

SD = standard deviation; CV = coefficient of variation; ICC = Intraclass correlation coefficient; CI = confidence interval; cm = centimeters; BJ = Broad jump; SBHR = Single broad hop right; SBHL = Single broad hop left; TBJ = Triple broad jump; TBHR = Triple broad hop right; TBHL = Triple broad hop left.

*Indicates a within subject effect (significant F); # indicates location of significant pairwise difference; ^ Indicates violation of sphericity.

4.5 DISCUSSION

This was the first study to assess the reliability of horizontal jumping and hopping using a protocol involving arm swing and two-foot landings during hopping. The main findings were: 1) a systematic change in the mean was observed between testing occasions 1-3 in the late pubertal group in all but the BJ test; and 2) all horizontal jumps and hops in both groups were found to have acceptable absolute and relative reliability. Even though there was evidence of systematic change in the mature group testing, their absolute consistency appeared better than the less mature group composed of pre-pubertal and early pubertal girls.

Difference in the mean was computed to detect systematic variations across testing sessions for each maturity group. No significant differences between testing occasions were observed in the less mature group. This finding indicates that there were no systematic changes between testing occasions when using the current study's horizontal jumping and hopping protocols in girls of pre-pubertal and early pubertal maturity status. Conversely, the significant differences between session one and three in the more mature group for SBHR, SBHL, TBHR, TBHL are indicative of systematic changes. It has been stated that systematic changes are due to the effects learning, order, motivation, or fatigue (Atkinson and Nevill, 1998, Hopkins, 2000). It is possible that learning effects were responsible for the more mature group findings since they decreased their mean difference between sessions two to three compared to session one to two (Lorger et al., 2012). The specific technique factors responsible for the learning effect remain uncertain. Hopping technique factors may have included the forward-backwards action of the swing leg or the appropriate swinging of the arms to align with the free leg action (Getchell and Robertson, 1989, Robertson and Halverson, 1988). Regarding jumping, Fernandez-Santos et al. (2018) reported that takeoff distance, take-off speed, shoulder angle at takeoff, landing distance and relative take-off height explained 84.4% of the variance in broad jump distance. Given the complexity of horizontal jumping and hopping and the possible learning effect during this study, a second familiarization session is recommended.

Upon further examination of the differences in reliability between maturity groups, the confidence intervals around the change in mean were generally narrower (smaller change in the raw data), with smaller standard deviations, indicating greater precision and confidence in the estimate for the more mature group (Koo and Li, 2016). That is, the variability in the less mature group was greater, as indicated by the means and SD of the consecutive paired sessions and confidence intervals of the mean difference. Furthermore, it was observed that the CVs of all hopping tasks were lower in the more mature group (CV = 3.15% to 3.75%), compared to the less mature group (CV = 4.01% to 7.46%). Similarly, the CVs of the jumping tasks for the more mature group (CV = 2.82% to 2.98%) were lower than those of the less mature group (CV = 2.91% to 3.13%). These findings regarding the reliability of varying maturity groups agree with Moeskops et al. (2018b) and Meylan et al. (2012) who demonstrated that the reliability of peak force and jumping distance respectively, were better in more mature (CV = 3.8% to 6%) youth compared to less mature youth (CV = 6.1% to 9.4%). Therefore, irrespective of the significant differences between session one and three in the more mature group, the outlined jump and hop protocols can be used reliably in late pubertal girls, provided two familiarization sessions are administered. These tests can also be used reliably in samples of less mature girls comprised of pre-pubertal and early pubertal girls.

No other researchers have assessed the reliability of differing maturity groups during horizontal hopping. Furthermore, only one study involved the assessment of the inter-day reliability of horizontal hopping during childhood in girls (McCubbine et al., 2018), while none have done so for adolescent girls. The current study and McCubbine et al. (2018) agree in terms of CVs for SBHR and SBHL (~4%). However, it was observed that TBHR (CV = 7.01%, ICC = 0.96) and TBHL (CV = 7.46%, ICC = 0.93) disagree with McCubbine et al. (2018) who reported a lower average CV% of 3.3% and 3.5% and ICCs of 0.72-0.87 for TBHR and TBHL respectively in 10-year-old girls. Given this higher within-subject variability for repetitive hopping, it may be that the more intense repetitive horizontal hopping tasks be administered before any jumping tasks, especially for less mature girls. This may limit fatigue and allow a participant to be more prepared to execute these higher difficulty tasks.

The CV values and the change in mean confidence intervals obtained in the current study offer insight into the magnitude of change necessary to signify meaningful training-related improvements in girls of varying maturity levels for horizontal jumping and hopping (Turner et al., 2015). For example, an improvement in BJ distance larger than the within-subject error of 2.91% for pre-pubertal and early pubertal group, would indicate a clinically meaningful change. Notably, the CVs and confidence intervals for jumps (BJ, TBJ) were generally lower compared to those for broad hops and triple broad hops. Consequently, a higher degree of training-related change would be necessary to observe meaningful significant improvements in hopping compared to jumping. Other researchers such as (Moeskops et al., 2022a, Fethney, 2010) observed a ~4.5% change in broad jump distance for a control group of eight-year-old physically active girls over a 10-month period. This increase does exceed the CV of broad jumps for the current study's lesser mature group.

Maturity-related differences have been previously reported for the broad jump test in girls. Moeskops et al. (2021) reported Cohen's d effect sizes for the broad jump test (distance) of 0.61 (95% CI = 0.21, 1.01) between early pre-pubertal and late pre-pubertal girls, $d = 0.18$ (95% CI = -0.35, 0.71) between late pre-pubertal to pubertal girls, and $d = 0.75$ (95% CI = 0.21, 1.29) between early pre-pubertal to pubertal girls. The effect sizes represent differences of 11.1%, 2.3%, and 13.6%, respectively. The reliability data established in this study enable a more accurate interpretation of training-related change. Training improvements above the reported typical error can be considered clinically significant. However, further interpretation may occur with comparison between maturity-related differences and training-related differences, where it has been shown by Moeskops et al. (2021) that a larger natural improvement in absolute broad jump distance may occur throughout the pre-pubertal period compared to the transition between the pre-pubertal period and pubertal period.

4.6 LIMITATIONS

There are certain limitations of this study worth considering. *Firstly*, one familiarization session may not have been sufficient, and this may have influenced the results by allowing a

possible learning effect to occur (Atkinson and Nevill, 1998). Thus, it is recommended to use two familiarization sessions when using these tests, most of which are under-researched in young girls. *Secondly*, the authors also submit that the focus on distance measurements alone restricts the analysis, as it precludes the assessment of kinetic or kinematic determinants of horizontal jumping and hopping ability. Nonetheless, it is important to note that the inclusion of these advanced analyses entails increased time and financial resources, which may not be practical or feasible for a broader range of practitioners. Despite these limitations, the data provided in this study offers a novel contribution to the existing literature by presenting straightforward and easily obtainable measurements, facilitating wider application in various professional settings. *Finally*, the sample size was insufficient to classify enough participants as mid-pubertal, limiting the data available to assess the reliability of horizontal jumping and hopping across a broader range of maturity statuses in girls. This study provides valuable data regarding the within-subject error associated with meaningful training-related changes in horizontal jumping and hopping distance (Turner et al., 2015).

4.7 CONCLUSION AND PRACTICAL APPLICATIONS

Regardless of jump/hop task or maturation group, all average CVs were under 10% and all average ICCs were greater than 0.9 (0.93-0.98), indicating acceptable absolute consistency and excellent agreement, respectively. Although significant differences were observed between sessions of the more mature group, there was strong consistency and agreement across the measurements. Therefore, all jumping and hopping tests in this study can be used to provide reliable information on girls of differing maturity status involved in sports with jumping and sprinting, so long as two familiarization sessions are used. The CV values reported in this investigation can provide insight into the variability above which training-related changes are considered clinically significant. More accurate interpretations of clinically significant training-related changes can better inform practitioners about the implications of specific training strategies. Future research recommendations include examining the effect of training on horizontal jumping and hopping tasks using the current study's testing protocols.

CHAPTER 5. VERTICAL AND LEG STIFFNESS DURING SPRINTING IN YOUTH FEMALE ATHLETES AT VARYING STAGES OF MATURITY

5.0 PRELUDE

Chapter 4 demonstrated acceptable absolute and relative reliability for all jumping and hopping protocols, with jumping tasks being more reliable than hopping tasks in girls. Specifically, the threshold for meaningful change (CV%) was lower for the broad jump and triple broad jump compared to the broad hop and triple broad hop. Similarly, Chapter 3 also demonstrated acceptable reliability for all vertical sub-maximal hopping tasks except for sub-maximal hopping on the non-dominant leg at 2.5 Hz. The CV values reported are indicative of the within-subject error that helps interpret training-related changes in leg stiffness beyond natural growth and maturation changes. Chapters 3 established the reliability of leg stiffness during sub-maximal hopping and previous literature established the reliability of sprinting using a floor-level optical measurement device in girls. However, leg stiffness during both fast-SSC tasks have not been evaluated for maturity-related differences. Therefore, Chapter 5 and 6 endeavored to explore the maturity-related differences during sprinting and unilateral sub-maximal hopping respectively. These natural changes can serve as a reference point depicting the expected variations in leg stiffness throughout normal growth and maturation, which can be used to indirectly compare training-induced adaptations and determine the effectiveness of training programs administered to girls of varying maturity status.

5.1 INTRODUCTION

Sprinting is a fundamental movement skill that is a key determinant of athletic development (Schepens et al., 1998). It involves elastic rebounds off the ground that help carry the body across the ground quickly (Meyers et al., 2016, Schepens et al., 1998, Cavagna et al., 1977). A key factor in the elastic rebound action is stiffness of the lower limbs, which describes the resistance to deformation under an applied force (Butler et al., 2003). Adequate stiffness of the lower limbs helps generate large and rapid forces to prevent excessive collapse of the leg and thus, the center of mass during the descent phase of ground contact in sprinting (Brughelli

and Cronin, 2008a, Bret et al., 2002). Moreover, stiffness enables elastic tissues, such as tendons, to enhance rate of force development and efficiently reuse stored elastic energy during the propulsive phase (Vaughn et al., 2013, Brughelli and Cronin, 2008a, Enomoto et al., 2019). This energy-saving mechanism along with reflex contributions and increased pre-phase muscle activity contributes to force potentiation and enhanced work output during the propulsive phase (Turner and Jeffreys, 2010, Brazier et al., 2017, van Ingen Schenau et al., 1997). Potentiation optimizes projection into the air and across the ground, providing sufficient time for the swing leg to reposition for the next step (Moir et al., 2018, Brughelli and Cronin, 2008a, Meyers et al., 2019, McMahon and Cheng, 1990, Meyers et al., 2017b). Ultimately, stiffness enhances sprinting by facilitating efficient force application during the ground contact phase, thereby increasing step frequency (Meyers et al., 2016), expanding stride length (McMahon and Cheng, 1990, Meyers et al., 2019), reducing ground contact time (Meyers et al., 2016) and improving running economy (Clark and Weyand, 2014, Moir et al., 2018, Cavagna et al., 1977).

Stiffness behavior is characterized by the complex interaction of muscles, tendons, ligaments, cartilage, and bones that all contribute to resisting deformation under an applied force (Butler et al., 2003, Brughelli and Cronin, 2008a, Brazier et al., 2017). However, describing the intrinsic stiffness behavior of each structure directly is overly complex, so a simpler biomechanical model is used to describe global forms of stiffness indirectly (McMahon and Cheng, 1990, Farley and Gonzalez, 1996). One such model, the spring-mass model, represents the body as a given mass supported by a spring, which corresponds to the leg (Brauner et al., 2014). This model illustrates how effectively the body manages downward forces to achieve subsequent upward propulsion. Furthermore, the spring mass model explains how stiffness enables the leg 'spring' to store elastic energy when compressed, building up force to resist deformation and control downward forces (Butler et al., 2003, Struzik et al., 2021). During the upward portion, the spring recoils and reutilizes elastic energy (Brughelli and Cronin, 2008a, McMahon et al., 2012). The spring-mass model has been adopted due to the feasibility of stiffness measures during athletic tasks in the field like sprinting and sub-maximal hopping (Kuzmeski et al., 2021).

The spring mass model helps calculate two forms of stiffness, vertical and leg stiffness. It uses spatio-temporal variables like contact time and flight time, as well as anthropometric variables like leg length and body mass, to estimate the deformation and model the applied force (Morin et al., 2005). Vertical stiffness refers to the resistance to displacement of the center of mass from vertical forces, while leg stiffness refers to the ratio of force applied during ground contact to compression of the leg spring (Brughelli and Cronin, 2008a, McMahon and Cheng, 1990). However, since the leg is moving forwards as it descends during sprinting, leg stiffness involves a vertical and horizontal component (Moresi, 2011, Farley and Gonzalez, 1996). The horizontal portion refers to the resistance to deformation from horizontal forces while the leg is in contact with the ground (Farley and Gonzalez, 1996, McMahon and Cheng, 1990). Therefore, unlike vertical hopping in place, vertical and leg stiffness during sprinting are distinct qualities that help control and coordinate the ground contact phase (Struzik et al., 2021).

Vertical and leg stiffness according to age and maturity status have been examined for their influence on sprinting in boys (Meyers et al., 2019, Meyers et al., 2015b, Meyers et al., 2016, Rumpf et al., 2013, Enomoto et al., 2019), and in pooled studies of girls and boys (Schepens et al., 1998). These studies found notable increases in relative vertical stiffness and speed during overground sprinting as maturity status progressed from pre-PHV to post-PHV (Meyers et al., 2016). Additionally, pre-PHV boys exhibited a significant rise in relative leg stiffness (RelKleg), relative max force and step length over time during overground sprinting, whereas no significant change was observed in boys transitioning from pre- to post-PHV for relative leg stiffness (Meyers et al., 2016). In a combined analysis of boys and girls, absolute vertical stiffness (Kvert) remained steady until age 12, after which it increased. Conversely, relative vertical stiffness (RelKvert) decreased during childhood and stabilized during adolescence (Schepens et al., 1998). The significant associations between absolute forms of stiffness with changes in speed, step frequency and contact time in boys, and the associations between relative leg stiffness with contact time (Meyers et al., 2016) underscore the importance of assessing stiffness qualities both absolutely and relatively during sprinting. It also provides insight into the effect of growth and maturation-related body size changes on stiffness qualities and sprint performance.

The effects of growth and maturation on sprinting development have been noted with researchers demonstrating peak speed increases with advancing maturity status in girls up to the pubertal stage (Moeskops et al., 2021). Similarly, it has been reported that speed in girls increases linearly with age during childhood and early adolescence, then plateaus thereafter (Nagahara et al., 2019, Sokołowski and Chrzanowska, 2012). However, maturity-related vertical and leg stiffness differences during sprinting have not been investigated in girls. Furthermore, the magnitude of difference in spatio-temporal variables with advancing maturity status is under-researched compared to boys. There is potential benefit of vertical and leg stiffness in improving sprint performance through better ground force application in girls. With the lack of studies examining stiffness variables and spatio-temporal variables during sprinting in girls, this study aims to investigate the maturity-related differences in absolute vertical and leg stiffness (Kleg), relative vertical and leg stiffness and spatio-temporal variables during a 20-meter sprint in youth female athletes.

5.2 METHODS

5.2.1 Participants

Thirty-one youth female volleyball players were recruited to participate in this study. Initial inclusion criteria included: a) participation in the highest national U13 youth level volleyball competition in Olomouc, Czechia; b) being free from major orthopedic injuries for at least 3 months prior to the start of the study; c) completing both the pre-test and post-test of a given assessment. Additional criteria involved being classified as either pre-pubertal (PRE), early pubertal (EPUB) or mid-pubertal (MPUB) and reaching maximum speed before the end of the 20-meter sprint. As a result, five participants were excluded based on maturity status, while one was excluded based on maximal speed within the requisite distance. These criteria left 25 participants for the final analysis. Participants were split into three maturity groups based on predicted adult height percentage (PAH%). These groups consisted of nine PRE girls, eight EPUB girls, and eight MPUB girls. The U13 criteria increased the likelihood that late-maturing MPUB girls would remain part of the study (Malina and Koziel, 2014). Participant characteristics for all groups are presented in Table 5.1. All participants and

parents/guardians were informed of the benefits and risks of being a part of this study. Written parental consent and written participant assent were obtained prior to data collection. All data collection procedures were reviewed and approved by the Institutional Research Ethics Committees (Reference codes 19/434; 15/2023) and the study was conducted in accordance with the declaration of Helsinki.

Table 5.1. Participant characteristics per maturity group

Variables	PRE (<i>n</i> = 9)	EPUB (<i>n</i> = 8)	MPUB (<i>n</i> = 8)
PAH %	81.62 ± 2.81	86.69 ± 1.50	93.65 ± 1.30
Body height (cm)	139.91 ± 7.70	147.94 ± 3.50	162.40 ± 5.31
SH (cm)	71.30 ± 3.69	73.90 ± 1.92	82.20 ± 1.92
LL (cm)	68.60 ± 4.77	74.04 ± 3.05	80.21 ± 4.12
BM (kg)	33.25 ± 6.34	41.40 ± 8.23	46.76 ± 6.81
BF%	18.79 ± 7.78	22.90 ± 9.32	17.58 ± 7.08
Age (years)	9.50 ± 0.73	10.50 ± 0.59	12.50 ± 0.76

PRE = pre-pubertal; EPUB = early pubertal; MPUB = mid-pubertal; PAH = predicted adult height; SH = seated height; LL = leg length; BM = Body mass; BF = body fat; *n* = number of participants.

5.2.2 Study procedures

The 20-meter sprint was administered as part of a larger testing battery over a two-day period during the 2023 volleyball season. Anthropometric measurements and the 20-meter sprint test occurred on day one. A full description of the remaining tests is outlined in Sylvester et al. (2024). Participants were asked to refrain from vigorous physical activity 24 hours prior to the testing sessions. Each testing session began with a standardized warm-up which involved problem-based games consisting of fundamental movement skills such as skipping, jogging, and shuffling. This was followed by dynamic stretching that targeted the calves, quadriceps, hamstrings, and adductors. The last portion of the warm-up consisted of vertical bilateral and unilateral sub-maximal hopping, a series of single and triple horizontal jumps and hops of progressive intensity and three sprints of progressive intensity (~60%, ~90%, and 100% of maximal effort).

5.2.3 Testing protocols

5.2.3.1 Anthropometric and maturity measures

Participant standing height and seated height were measured using a stadiometer (Seca 213, Portable Stadiometer), using the protocols described by Simmons (2000). Leg length (cm) was calculated by subtracting seated height from standing height. Body mass (kg) and body fat percentage were quantified using a Bioelectric Impedance Analysis device (Tanita® Sc-240, Tanita Corporation, Tokyo, Japan). Maturity status was assessed by using the spreadsheet by Towlson et al. (2020) to calculate predicted adult height percentage (PAH%) based on the method by (Khamis and Roche, 1994). Participants with a PAH% < 85% was considered pre-pubertal (PRE), $\geq 85\%$ and < 90% was considered in the early pubertal stage (EPUB), $\geq 90\%$ but < 95% was considered mid-pubertal (MPUB) (Cumming et al., 2017). The mean PAH% for each maturity group is presented in Table 5.1.

5.2.3.2 20-meter sprint procedures

Maximal sprints were completed by sprinting over 20 meters through a floor level optical measurement system (Optojump, Microgate, Italy) positioned from the 5-meter mark to the 20-meter mark. Participants were directed to assume a split stance starting position, with their preferred front foot positioned just behind the starting line. They were instructed to get "down and ready", then remain "still like a statue". Once motionless, the researcher then signaled, "go whenever you want," allowing participants to initiate the sprint at their own discretion. To ensure maximal effort throughout the entire 20-meter sprint, participants were instructed to run an additional two and a half meters beyond the finish line, which was marked by a pylon. Researchers have suggested that young female athletes (~age 7-13 years) can achieve their maximum speed within a 20-meter distance (Moeskops et al., 2021). Each participant completed three maximal sprints, with three minutes of passive recovery between each sprint. Sprint data were instantaneously collected to an accuracy of 1/1000 s using the Optojump Next software (Microgate, Italy), and subsequently exported to Microsoft Excel® 2015 for data processing.

5.2.3.3 Data analyses

Sprint data obtained from the Optojump included step by step spatio-temporal variables such as contact time (s), flight time (s), step frequency (stride/s), step length (m), and speed (m/s). The two fastest consecutive steps were identified to be considered for analysis. If it was determined that the participant obtained their fastest step from the last foot contact in the collection zone or they were still accelerating incrementally at the end of the collection period, these data and participants were excluded (Meyers et al., 2015b, Meyers et al., 2016). These criteria resulted in one participant being removed, leaving 25 participants for analysis. All data from the two fastest steps of each trial were averaged and used for analysis, where all stiffness variables and spatio-temporal sprint variables were calculated using a customized Microsoft Excel spreadsheet (Meyers et al., 2015b, Meyers et al., 2016). Once the stiffness variables were calculated for each trial, data from all three trials were averaged, where these values served as the final values for analysis. Trials were averaged to reduce the level of variability in the data (Meyers et al., 2015b). Acceptable reliability has been reported (CV, ICC) for the use of floor-level optical measurement systems in youth female athletes for

speed, contact time, flight time, step length, and step frequency during sprinting (CV = 1.7 to 5.7%) in mid-PHV and post-PHV girls (Talukdar et al., 2021b). However, the current study included girls of pre-pubertal, early pubertal, and mid-pubertal status. Therefore, inter-trial reliability tests were conducted among these different maturity groups.

Stiffness variables were calculated using the methods outlined by Morin et al. (2005), in which the ground reaction force over time is modeled using a sine-wave function (Morin et al., 2005, Dalleau et al., 2004, Kram and Dawson, 1998, Alexander, 1989). Detailed calculations are listed in Equations 1-5. First, the ratio of vertical force to vertical displacement of the center of mass, known as vertical stiffness, was calculated using Equation 1. In this equation, F_{\max} = maximal vertical ground reaction force (newtons) and Δy = peak center of mass displacement (m). Vertical stiffness is measured in kilonewtons per meter (kN/m).

$$K_{\text{vert}} = \frac{F_{\max}}{\Delta y}$$

Equation 1

Maximal modelled ground reaction force during ground contact measured in kilonewtons (kN), was calculated using Equation 2. In this equation, M is the participants' body mass (kg), g = acceleration due to gravity (m/s^2), T_c = contact time (s), T_f = flight time (s), π = half period of the sine wave.

$$F_{\max} = Mg \frac{\pi}{2} \left(\frac{T_f}{T_c} + 1 \right)$$

Equation 2

The displacement of the center of mass from initial touchdown to its lowest point during ground contact measured in meters (m), known as the peak center of mass displacement (Δy), is presented in Equation 3. In this equation F_{\max} = maximal vertical ground reaction force

(newtons), M = body mass (kg), T_c = contact time (s), g = acceleration due to gravity (m/s^2), π = half period of the sine wave.

$$\Delta y = \frac{F_{max}}{M} \times \frac{T_c^2}{\pi^2} + g \frac{T_c^2}{8}$$

Equation 3

Leg stiffness calculations during running, involve determining the ratio between maximal force and change in leg length (Farley and Gonzalez, 1996). Equation 4 can be used to calculate leg stiffness where K_{leg} = leg stiffness, F_{max} = maximal force, ΔL = change in leg length.

$$K_{leg} = \frac{F_{max}}{\Delta L}$$

Equation 4

The difference in standing leg length to the length when the center of mass reaches maximum displacement is calculated using Equation 5, where ΔL = change in leg length (m), L = standing leg length (m), T_c = contact time (s), v = velocity (m/s), and Δy = center of mass displacement (m).

$$\Delta L = L - \sqrt{L^2 - \left(\frac{vT_c}{2}\right)^2} + \Delta y$$

Equation 5

Relative forms of stiffness were calculated by multiplying absolute stiffness by the quotient of leg length and body mass multiplied by gravitational acceleration of 9.81 ms^{-2} (McMahon and Cheng, 1990).

5.3 STATISTICAL ANALYSES

Statistical analyses were completed within SPSS 29 (version 29; SPSS Inc, Chicago, IL). To investigate the effect of maturity status on the magnitude of difference in absolute and relative vertical and leg stiffness, a one-way analysis of variance (ANOVA) of between group effects was employed. Maturity groups, PRE, EPUB, MPUB, served as between-subject factors, while K_{vert} and $RelK_{vert}$, and K_{leg} and $RelK_{leg}$, served as the dependent variables. To identify the origin of the differences, a Bonferroni post hoc test was employed. Additionally, Hedges' g effect sizes with 95% confidence intervals (CI) were used to quantify the degree of difference between maturity groups using a customized spreadsheet (Cambridge, 2024). Interpretation of the magnitude of Hedges' g were based on the following thresholds: trivial 0.00–0.19, small 0.20–0.49, moderate 0.50–0.79, and large ≥ 0.80 (Cohen, 1988). To assess the magnitude of difference, statistical significance was set at $p < 0.05$. The data were examined to confirm parametric assumptions such as, normality of the dependent variable for each group using the Shapiro-Wilk test of normality (Razali and Wah, 2011), a Quantile-quantile plot of the standardized residuals (Harrison et al., 2018), Z scores for skewness and kurtosis, and extreme outliers in the interquartile (box and whiskers) plot (Cain et al., 2017, Statology, 2022, Ghasemi and Zahediasl, 2012). Additionally, homogeneity of variance using Levene's test of equality of variances was verified. The EPUB group for absolute and relative leg stiffness variables revealed Shapiro-Wilk violations. Otherwise, all assumptions were met resulting in data suitable for analysis.

Inter-trial reliability for all stiffness tests and spatio-temporal sprint variables were determined using a repeated measures analysis of variance (RMANOVA) of within-subject effects across maturity stages: prepubertal (PRE), early pubertal (EPUB), and mid pubertal (MPUB). Bonferroni post hoc analysis was used to examine the origin of any systematic difference between the test trials (Atkinson and Nevill, 1998). Average CV% with 95% confidence intervals (CI) were used to determine absolute reliability. Values for CV of $< 10\%$ were considered acceptable reliability (Maloney et al., 2015). Data were verified for homogeneity of variance of the differences using a Mauchly's test of Sphericity (Blanca et al., 2023). Where sphericity assumptions were violated, the Greenhouse-Geisser statistic was interpreted. To assess reliability, statistical significance was set at $p < 0.05$.

A priori sample size was determined using G*Power version 3.1.9.7 (Faul 2007). Statistical significance was set at $\alpha = 0.05$, power was set at $1-\beta = 0.80$, using three groups, with effect size set at $d = 0.5$, roughly equivalent to that seen in (Meyers et al., 2019). Using these parameters, the required sample size was 42 participants. With only 25 participants, this requirement was not satisfied.

5.4 RESULTS

One-way ANOVA data on absolute and relative vertical and leg stiffness for each maturity group are presented in Table 5.2. This data includes the mean, SD, mean difference with 95% confidence intervals, and Hedges' g effect size with 95% confidence intervals. Significant pairwise differences were noted for Kvert, Kleg, RelKvert, and RelKleg, and speed between PRE and MPUB. The findings for maturity group differences are presented in Table 5.2 and Figure 5.1. CV values for absolute and relative vertical stiffness were $< 10\%$, while CV values for absolute and relative leg stiffness were between 11-16% (Table 5.3).

5.4.1 Vertical and leg stiffness differences

Significant maturity-related differences (significant F-value) were noted for Kvert ($p = 0.003$), Kleg ($p = 0.006$), RelKvert ($p = 0.003$), and RelKleg ($p = 0.006$). ANOVA post hoc tests revealed a significant difference with large effects between PRE and MPUB for absolute vertical stiffness ($g = 1.63$, 95% CI = 0.54, 2.73, $p < 0.01$), absolute leg stiffness ($g = 1.51$, 95% CI = 0.43, 2.59, $p < 0.01$), relative vertical stiffness ($g = 1.64$, 95% CI = 0.54, 2.74, $p < 0.01$), and relative leg stiffness ($g = 1.51$, 95% CI = 0.43, 2.59 $p < 0.01$). There were no other significant pairwise differences between any other maturity groups. Reliability analysis revealed no significant pairwise differences for Kvert, Kleg, RelKvert, and RelKleg in the RMANOVA. Additionally, CVs ranged between 3.06-6.24% for Kvert and RelKvert, whereas the CVs ranged from 11.37-15.46% for Kleg and RelKleg. Sphericity was violated by Kleg and RelKleg. In these cases, the F-value of the Greenhouse-Geisser statistics were interpreted showing no significant difference.

5.4.2 Spatio-temporal variable differences

There were significant differences (significant F-value) between maturity groups for speed ($p = 0.006$). ANOVA post hoc differences for speed were noted between PRE and MPUB ($g = 1.66$, 95% CI = 0.55, 2.76, $p < 0.01$, large effect) and between EPUB and MPUB (1.11, 95% CI = 0.05, 2.15, $p < 0.05$). There were no maturity-related differences for CT, SF, FT. Finally, although one-way ANOVA findings revealed an overall significant F-value ($p = 0.018$) for SL, and a significant post hoc difference between PRE and MPUB ($g = 1.79$, 95% CI = 0.67, 2.92, $p < 0.01$, large effect), this variable did display a significant difference between trial one and three in the RMANOVA, and an average CV% that ranged from 2.08-2.39%. Additionally, the reliability analysis revealed no significant pairwise differences for CT, FT, speed, while a significant F-value ($p = 0.008$) and significant pairwise differences were detected for SF between trial 1-3 ($p = 0.046$) and 2-3 ($p = 0.023$).

Table 5.2. Group differences in stiffness and sprint spatio-temporal variables using Hedges' *g* effect size and 95% CI

Variable	PRE -EPUB								
	PRE Mean + SD	EPUB Mean + SD	MPUB Mean + SD	PRE-EPUB D/f (95% CI)	ES (95% CI)	EPUB - MPUB D/f (95% CI)	EPUB – MPUB ES (95% CI)	PRE - MPUB D/f (95% CI)	PRE - MPUB ES (95% CI)
Kvert (kN/m)	24.48 ± 5.65	28.71 ± 4.11	34.88 ± 6.45	4.23 (-2.69, 11.15)	0.80 (-0.19, 1.79)	6.18 (-0.94, 13.3)	1.08 (0.03, 2.13)	10.41 [◊] (3.49, 17.33)	1.63 (0.54, 2.73)
Kleg (kN/m)	6.09 ± 1.32	7.94 ± 1.37	8.78 ± 2.03	1.85 (-0.16, 3.86)	1.31 (0.26, 2.36)	0.84 (-1.22, 2.91)	0.46 (-0.53, 1.45)	2.69 [◊] (0.69, 4.70)	1.51 (0.43, 2.59)
RelKvert	54.60 ± 12.61	64.04 ± 9.16	77.82 ± 14.39	9.44 (-6.00, 24.88)	0.80 (-0.19, 1.79)	13.78 (-2.11, 29.67)	1.08 (0.03, 2.13)	23.22 [◊] (7.78, 38.66)	1.64 (0.54, 2.74)
RelKleg	13.59 ± 2.94	17.71 ± 3.06	19.59 ± 4.52	4.13 (-0.35, 8.60)	1.30 (0.26, 2.35)	1.88 (-2.73, 6.48)	0.46 (-0.53, 1.45)	6.01 [◊] (1.53, 10.48)	1.51 (0.43, 2.59)
Speed (m/s)	5.64 ± 0.36	5.83 ± 0.5	6.44 ± 0.55	0.19 (-0.40, 0.78)	0.42 (-0.54, 1.38)	0.61* (0.00, 1.22)	1.10 (0.05, 2.15)	0.80 [◊] (0.21, 1.39)	1.66 (0.55, 2.76)
T _c (s)	0.16 ± 0.01	0.16 ± 0.02	0.16 ± 0.01	0.00 (-0.015, 0.02)	0.13 (-0.82, 1.08)	-0.01 (-0.00, 0.01)	-0.42 (-1.41, 0.57)	0.01 (-0.02, 0.01)	-0.29 (-1.25, 0.67)
T _f (s)	0.10 ± 0.01	0.11 ± 0.02	0.11 ± 0.02	0.01 (-0.01, 0.03)	0.69 (-0.29, 1.67)	0.00 (-0.02, 0.02)	0.06 (-0.92, 1.04)	0.01 (-0.01, 0.03)	0.80 (-0.19, 1.79)
SL (m)	1.49 ± 0.12	1.60 ± 0.17	1.73 ± 0.14	0.11 (-0.07, 0.30)	0.73 (-0.25, 1.72)	0.13 (-0.05, 0.32)	0.81 (-0.21, 1.83)	0.25 [◊] (0.06, 0.43)	1.79 (0.67, 2.92)
SF (steps/s)	3.82 ± 0.27	3.67 ± 0.24	3.72 ± 0.23	-0.15 (-0.46, 0.16)	-0.57 (-1.54, 0.40)	0.06 (-0.26, 0.38)	0.23 (-0.75, 1.22)	-0.09 (-0.41, 0.22)	-0.36 (-1.32, 0.60)

PRE = pre-pubertal (*n* = 9); EPUB = early pubertal (*n* = 8); MPUB = mid-pubertal (*n* = 8); SD = standard deviation; ES = effect size; CI = confidence interval; Kleg = absolute leg stiffness; Kvert = absolute vertical stiffness; RelKvert = relative vertical stiffness; RelKleg = relative leg stiffness; T_c = contact time; T_f = flight time; D/f = raw difference; kN/m = kilonewtons per meter; *n* = number of participants.

* = significant difference (*p* < 0.05)

◊ = significant difference (*p* < 0.01)

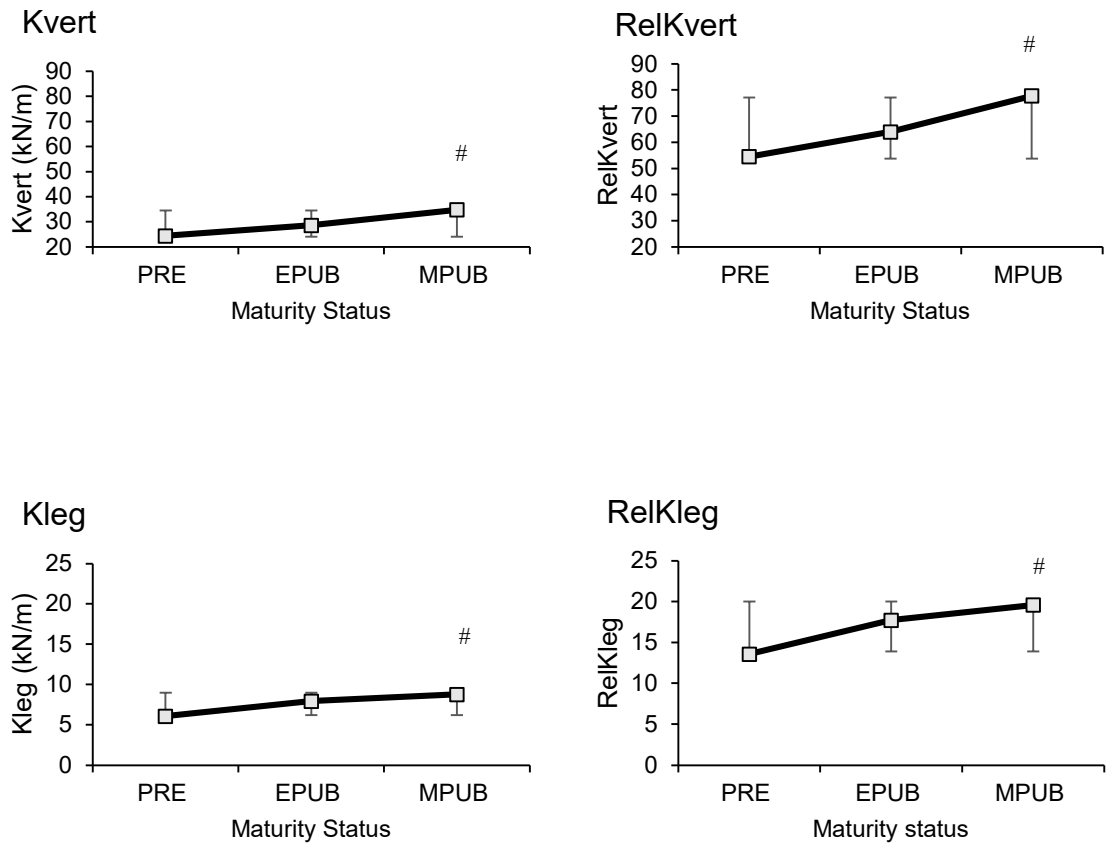


Figure 5.1. Maturity group differences for vertical and leg stiffness- Absolute vertical stiffness, relative vertical stiffness, absolute leg stiffness, relative leg stiffness.

Kvert = absolute vertical stiffness; Kleg = absolute leg stiffness; RelKvert = relative vertical stiffness; RelKleg = relative leg stiffness; PRE = pre-pubertal girls; MPUB = mid-pubertal girls; LPUB = Late pubertal girls; kN/m = kilo newtons per meter.

= significant difference from PRE and MPUB ($p < 0.01$)

Table 5.3. Average CV% + 95% confidence intervals for stiffness and spatio-temporal variables

Variable	PRE (<i>n</i> = 9)	EPUB (<i>n</i> = 8)	MPUB (<i>n</i> = 8)
Kvert (kN/m)	3.93 (2.58, 5.28)	3.06 (1.80, 4.32)	6.24 (3.66, 8.82)
Kleg (kN/m)	11.37 (5.48, 17.27)	15.46 (7.15, 23.77)	13.84 (7.29, 20.38)
RelKvert	3.93 (2.58, 5.28)	3.06 (1.80, 4.32)	6.24 (3.66, 8.82)
RelKleg	11.37 (5.48, 17.27)	15.46 (7.15, 23.77)	13.84 (7.29, 20.38)
CT (s)	2.82 (1.94, 3.70)	2.77 (1.61, 3.92)	4.47 (2.54, 6.41)
FT (s)	7.69 (3.78, 11.60)	8.69 (4.40, 12.97)	6.91 (3.31, 10.52)
SF (s)	2.64 (1.42, 3.87)	2.70 (1.63, 3.78)	3.00 (1.86, 4.14)
SL (m)	2.11 (0.97, 3.24)	2.08 (1.35, 2.82)	2.39 (1.35, 3.42)
Speed (m/s)	1.97 (1.23, 2.72)	2.07 (1.16, 2.98)	1.37 (0.73, 2.01)

K = stiffness; vert = vertical; T_c = contact time; T_f = flight time; SL = step length; CV = coefficient of variation; PRE = pre-pubertal; EPUB = early pubertal; MPUB = mid-pubertal; kN/m = kilonewtons per meter; *n* = number of participants.

5.5 DISCUSSION

This was the first study to examine maturity-related differences in global stiffness measures in girls during sprinting. These findings provide insight into the expected degree of difference in global stiffness measures during sprinting in girls. Significant differences in K_{vert} and $RelK_{ert}$, as well as K_{leg} and $RelK_{leg}$, were present between the PRE and MPUB stages during sprinting (Table 5.2). This study also reported findings on sprint speed and sprint spatio-temporal variables. It was revealed that speed and SL differed significantly between PRE and MPUB whereas SF, T_c and T_f did not differ between any maturity groups.

5.5.1 Absolute and relative vertical stiffness

The current investigation was able to show how the ability to resist the downward displacement of the center of mass during sprinting differs with advancing maturity status in girls. The difference between PRE and MPUB for K_{vert} was large and significant, while all other K_{vert} pairwise differences were large and non-significant. Additionally, the effect sizes for K_{vert} from PRE to EPUB ($g = 0.8$, 95% CI = -0.19, 1.79) were smaller than those between EPUB and MPUB ($g = 1.08$, 95% CI = 0.03, 2.13). While there are no studies in girls which have examined K_{vert} by maturity status during sprinting, previous studies in boys have noted maturity and age-related differences in K_{vert} during sprinting (Meyers et al., 2019, Rumpf et al., 2013). More specifically, Rumpf et al. (2013) noted significant differences between pre-PHV, mid-PHV and post-PHV athletic boys during a 30-meter non-motorized treadmill sprint. These findings along with the current findings underscore the importance of considering maturity status during training to improve K_{vert} for girls during sprinting. The findings also suggest that there are body size factors like body mass and leg length that influence K_{vert} . For instance, Schepens et al. (1998) investigated vertical stiffness differences with age during running and found that K_{vert} is similar among children but increases significantly after about 12 years of age. They attributed this increase to the substantial gains in body mass after age 12. This rise in stiffness is needed to maintain a high force to deformation ratio, characteristic of a more elastic rebound action off the ground during fast-SSC tasks (Beerse and Wu, 2016). However, there are mechanisms that influence

stiffness which do not rely on body size (Lloyd et al., 2011b). To account for these influences, RelKvert was assessed.

Similar to Kvert, a significant difference with a large effect size was noted for RelKvert between PRE and MPUB ($p < 0.05$). The current findings align with the longitudinal study of Meyers et al. (2016), who noted a significant increase in RelKvert during sprinting as boys transitioned from pre- to post-peak height velocity (PHV) stages. Furthermore, despite boys generally having larger body sizes during adolescence (Naughton et al., 2000), the stiffness values of girls from the present study (54.6-77.82 units), were comparable to those of boys (71.8-76.8 units) from Meyers et al. (2019). The current findings and previous literature suggest there are body size-independent factors that impact stiffness. These elements include muscle preactivation and stretch-reflex influence which increase extensor muscle activity during ground contact (Schepens et al., 1998, Sudlow et al., 2024, Oliver and Smith, 2010).

Notably, the reliability analysis revealed no significant pairwise differences for Kvert, Kleg, RelKvert, and RelKleg between maturity groups. Additionally, average CVs ranged between 3.06% to 6.24% for Kvert and RelKvert, indicating acceptable reliability. Puberty plays a crucial role in the development of Kvert and RelKvert during sprinting in both boys and girls, given the significant change at the MPUB stage. Understanding maturity-related differences in Kvert and RelKvert is essential for practitioners to tailor training programs that accommodate the evolving growth and maturation of young girls.

5.5.2 Absolute and relative leg stiffness

The pattern of maturity-related Kleg discrepancies was different compared to that of Kvert. The largest discrepancy was observed between the PRE and MPUB stages ($g = 1.51$, 95% CI = 0.43, 2.59). Meanwhile, the difference between EPUB and MPUB was smaller in magnitude ($g = 0.46$, 95% CI = -0.53, 1.45) compared to the degree of difference between PRE and EPUB ($g = 1.31$, 95% CI = 0.26, 2.36). No researchers have examined Kleg during sprinting in girls. Although, previous researchers have reported larger Kleg in post-PHV boys

compared to pre-PHV and mid-PHV boys (Rumpf et al., 2013). Additionally, mean Kleg values were reported as 3.88 kN/m for children in Heise and Bachman (2000), whereas leg stiffness in the present study was 6.09-8.78 kN/m. The smaller magnitude of difference in Kleg from EPUB to MPUB in the present study may reflect an adjustment period to changes in leg length, muscular strength, body mass and other size-related tissue factors, like increased tendon cross-sectional area (Sudlow et al., 2024, Laffaye et al., 2016).

RelKleg in the present study revealed a similar trend to Kleg, in which the difference between PRE and EPUB was larger than that of EPUB to MPUB. Furthermore, the largest difference was still between PRE and MPUB. This trend somewhat concurs with a longitudinal investigation in boys by Meyers et al. (2016). This longitudinal study described how RelKleg improved significantly with time in boys that maintained pre-PHV status but plateaued for boys that experienced PHV. The present study did not include participants who had experienced PHV, so comparison between it and previous literature is difficult. However, both findings point to a large development of RelKleg during childhood, similar to that of sub-maximal hopping in boys (Lloyd et al., 2011b). Once again, relative values (RelKleg) of the present study (13.59-19.59 units) were comparable to those of boys (15.9-20.9 units) (Meyers et al., 2019). Together, the leg stiffness findings of the present study and previous literature suggest that the MPUB stage is crucial for the development of leg stiffness in girls leading to larger values in adolescents compared to children. The leg stiffness findings must be interpreted with caution given that Kleg and RelKleg displayed CV values between 11-16%. It appears that leg stiffness, which involves both a vertical and horizontal component (Farley and Gonzalez, 1996), is harder to capture reliably using this study's protocol. Understanding these nuances is crucial for designing training programs that appropriately address the evolving physical capabilities of young girls.

5.5.3 Speed and spatio-temporal variables

Significant differences in speed with moderate and large effect sizes were noted between EPUB and MPUB ($g = 1.10$, 95% CI = 0.05, 2.15) and between PRE and MPUB respectively. Furthermore, the difference in speed between PRE and EPUB ($g = 0.42$, 95% CI = -0.54,

1.38) was small and non-significant. The maturity-related differences in speed observed in this study are consistent with findings in girls from Moeskops et al. (2021) and Colyer et al. (2020), who demonstrated maturity-related speed differences during 20-meter and 30-meter sprints, respectively. Moeskops et al. (2021) found significant differences between late pre-pubertal girls and mid-pubertal girls across all sprint intervals (0-5, 5-10, 10-15, and 15-20 meters) with effect sizes ranging from small to large ($d = 0.35-0.95$). Similarly, Colyer et al. (2020) observed significant maximum velocity differences between consecutive maturity groups representing -2.17 (calendar age of 9.75 years) and -1.15 years (calendar age of 10.78 years) before PHV in girls respectively. Furthermore, average velocity demonstrated a moderate to large effect size between consecutive maturity groups representing -1.15 (calendar age of 10.78 years) and -0.11 years (calendar age of 11.55 years) from PHV respectively. Additionally, Nagahara et al. (2019) demonstrated age-related improvements in average speed, noting a higher rate of increase before age 12.7 compared to after. This age approximately corresponds with the maturity-related speed differences observed in the current study (under 12.5 years of age) and previous research (Colyer et al., 2020, Moeskops et al., 2021). The current and previous studies underscore the influence of maturity status on speed. Given these maturity-related differences in sprint performance, further exploration of the determining factors of sprinting helped elucidate this relationship between maturation and sprinting in this study.

In the present study, there were no differences in SF, T_f or T_c based on maturity status. However, there was a significant difference in SL between PRE and MPUB ($g = 1.79$, 95% CI = 0.67, 2.92). These findings suggest that SL may impact increases in speed with advancing maturity status between PRE and MPUB. The significant difference in SL concurs with a longitudinal study on speed and underlying determinants in boys. This previous study reported that SL during a 30-meter sprint increased significantly over time in pre-PHV boys and boys that transitioned from pre-PHV to post-PHV (Meyers et al., 2016). Moreover, Talukdar et al. (2021b) demonstrated significant differences in SL between mid-PHV and post-PHV girls during a 30-meter sprint. The changes in SL and speed might be attributable to various physiological and physical developments during puberty like changes in relative maximal force, propulsive impulse, and stature (Sudlow et al., 2024, Colyer et al., 2020, Oliver and Smith, 2010, Meyers et al., 2016, Nagahara et al., 2019). In addition to the

maturity-related differences in spatio-temporal variables, it was discovered that SF and SL exhibited a systematic difference between paired trials, while all other variables did not. These significant differences were despite the average CV% for SF and SL remaining below 5%. Therefore, these spatio-temporal sprint variables should be interpreted with caution.

5.6 LIMITATIONS

A few limitations merit consideration within the present study. *Firstly*, as skeletal age assessments are regarded as the gold standard for measuring biological maturation, their absence in this study necessitated the use of a non-invasive estimation of maturity status. It is worth noting that this method exhibits a lower margin of error in girls compared to other non-invasive approaches (Lloyd et al., 2014b). *Secondly*, maturity status is recognized as a reflection of the current state of maturation at the time of assessment. It offers a broad overview of an individual's development rather than capturing the dynamic changes that would be observed in a longitudinal study (Lloyd et al., 2014b, Cumming et al., 2017). Nevertheless, this study stands as the inaugural investigation into maturity-related disparities in absolute and relative vertical and leg stiffness among girls during sprinting. *Thirdly*, the use of a floor-level optical measurement device limits the direct measurement of force-time variables which could provide insight into key stiffness determinants like vertical ground reaction force (Nagahara and Zushi, 2016). While the sine function employed to model maximal force in the vertical and leg stiffness equations may lack the precision of direct force measurement, it remains a valid and reliable method for assessing stiffness during sprinting (Meyers et al., 2019, Morin et al., 2005). It is acknowledged that this study was underpowered and may have limited the strength of the evidence supporting a null hypothesis in certain cases. It is presumed that one possible type 2 error originated from the non-significant differences in RelKleg. Despite the large ES between PRE and EPUB for and RelKleg ($g=1.3$, 95% CI = 0.26, 2.35), and the confidence intervals that did not cross zero, this parameter was still found non-significant. Furthermore, the confidence intervals were not substantially different from the other stiffness parameters. Overall, these findings do not concur with those reported in pre-PHV boys where RelKleg experienced a significant increase over a 21-month period during sprinting. Other parameters that may have been underpowered were Kleg and RelKleg between EPUB and MPUB. After a post hoc power analysis, the power was 0.47,

indicating low power. Furthermore, sprint speed and SF between PRE and EPUB produced a post hoc power of 0.4 and 0.66 respectively. Although confidence in the differences for these variables is low, moderate to large changes (significant) in average velocity in girls between a maturity offset of -1.15 years (calendar age of 10.78 years) and -0.11 years (calendar age of 11.55 years) from PHV (Colyer et al., 2020), roughly aligns with the current study's results with the larger EPUB to MPUB difference.

5.7 CONCLUSION AND PRACTICAL RECOMMENDATIONS

This study was able to provide insight into the maturity-related development of absolute and relative vertical and leg stiffness as well as speed and spatio-temporal sprint variables. All stiffness variables differed significantly between the PRE and MPUB maturity group, which reflects the influence of changes in anthropometric factors regarding absolute stiffness development and neuromuscular factors concerning relative stiffness development during sprinting in girls. The findings of this study suggest that the mid-pubertal stage is key in the development of absolute and relative vertical stiffness variables during sprinting in girls. Meanwhile, absolute and relative leg stiffness may develop to a greater degree in the early stages then decline in the magnitude of difference thereafter. Tailoring training programs to target adaptations in stiffness beyond natural developments may benefit sprinting ability in girls. Improved absolute and relative vertical and leg stiffness due to training may help offset rapid body mass increases that occur during puberty in girls. As a result, girls may be able to prevent excessive collapse of the center of mass and leg during sprinting and improve sprint performance.

CHAPTER 6. LEG STIFFNESS IN GIRLS OF DIFFERENT MATURITY STATUS AND ITS CONTRIBUTION TO SPRINTING PERFORMANCE

6.0 PRELUDE

Chapter 5 explored how maturity status influenced differences in absolute vertical and leg stiffness (K_{vert} and K_{leg} respectively), relative vertical and leg stiffness ($RelK_{vert}$ and $RelK_{leg}$ respectively), and spatio-temporal factors during sprinting in young girls. Significant pairwise differences were shown between pre-pubertal (PRE) and mid-pubertal (MPUB) for K_{vert} , K_{leg} , $RelK_{vert}$, $RelK_{leg}$, speed, step length (SL) but not contact time (CT), step frequency (SF), or flight time (FT). Reliability was deemed acceptable for K_{vert} , K_{leg} , $RelK_{vert}$, $RelK_{leg}$, CT, FT, and speed based on the absence of significant pairwise differences between maturity groups. However, SL was significantly different between trial one and three of the RMANOVA and SF showed significant differences between trials 1-3 and 2-3. Moreover, the coefficients of variation (CVs) ranged from 11.37-15.46% for K_{leg} and $RelK_{leg}$ and 3.06-6.24% for K_{vert} and $RelK_{vert}$. These findings, combined with confidence intervals for many pairwise comparisons crossing zero, suggest that maturity-related assessments of K_{leg} and $RelK_{leg}$ during sprinting in girls must be interpreted with caution.

Sprinting requires unilateral force production and a substantial contribution of ankle stiffness. In absence of ankle stiffness measurements, sub-maximal hopping, an ankle dominant movement and very suitable field-based leg stiffness measurement task, can indirectly provide insight into stiffness behavior at the ankle. However, maturity-related differences in leg stiffness during unilateral sub-maximal hopping, which may manifest differently compared to sprinting, have not been explored in girls. Therefore, Chapter 6 aimed to investigate leg stiffness differences in girls during unilateral sub-maximal hopping to understand how maturity might influence leg stiffness development in young girls.

6.1 INTRODUCTION

Stiffness is a key mechanical quality that helps control and coordinate the stretch-shortening cycle (SSC) during the ground contact phase of vertical hopping and sprinting (Maloney and Fletcher, 2018). Stiffness refers to the ability to resist deformation under an applied force (Butler et al., 2003, Brughelli and Cronin, 2008a), while the SSC refers to the coupling of an active muscle stretch followed by an explosive muscle shortening (Turner and Jeffreys, 2010). Differences in SSC performance between maturity stages have been described by jumping height and vertical stiffness (Sayer et al., 2018, Moeskops et al., 2020, Westbrook et al., 2020, Moeskops et al., 2021, Pedley et al., 2021). For example, Moeskops et al. (2020) observed a difference in relative vertical stiffness during drop jumping between early pubertal and pubertal girls. Meanwhile, Laffaye et al. (2016) reported that absolute leg stiffness increased non-linearly during adolescence and peaked between 15-16 years of age in girls during maximal hopping. In contrast, Lehnert et al. (2020) reported how absolute leg stiffness plateaued in 15–16-year-old girls (Maturity offset = 0.9 to 1.7 years) during bilateral sub-maximal hopping. Furthermore, it has been shown that relative leg stiffness during sub-maximal and maximal hopping experience larger declines and longer plateaus during adolescence compared to absolute leg stiffness (Laffaye et al., 2016, Lehnert et al., 2020, Lloyd et al., 2011b).

Sub-maximal hopping has been considered the most suitable assessment of leg stiffness due to its high force to deformation ratio, allowing optimal energy storage-reutilization, which facilitates spring-like applications of ground force and effective rebounding off the ground (Maloney and Fletcher, 2018, Lloyd et al., 2009, Beerse and Wu, 2016, Lloyd et al., 2012a). This is especially true when hopping at 2.5 Hz, the preferred frequency in youth (Granata et al., 2002, Beerse and Wu, 2016). The extant literature has revealed that during sub-maximal hopping, ankle joint stiffness is prominent and is a major modulator of leg stiffness (Farley and Morgenroth 1999). Moreover, absolute leg stiffness is significantly lower in children, but relative leg stiffness is significantly higher at the preferred frequency for bilateral and unilateral sub-maximal hopping (Beerse and Wu, 2016, Waugh et al., 2017). These differences in absolute and relative leg stiffness between children and adults indicate that there are anthropometric and neuromuscular factors that may influence absolute and relative

leg stiffness development (Radnor 2017). However, solely focusing on child-adult differences and existing studies on developmental leg stiffness in boys may be insufficient for fully understanding the progression of leg stiffness development. Researchers also have yet to evaluate differences in leg stiffness in girls of different maturity status during unilateral sub-maximal hopping at 2.5 Hz (Lloyd et al., 2011b, De Ste Croix et al., 2021). Therefore, the existing literature in girls, examining bilateral sub-maximal hopping at 2.5 Hz (Lehnert et al., 2020, De Ste Croix et al., 2017, De Ste Croix et al., 2018, Moeskops et al., 2018a), and unilaterally at 2.2 Hz (Waxman et al., 2018, Eiling et al., 2007), may be insufficient to understand leg stiffness development in girls.

Researchers have stated the importance of being able to express force and power unilaterally during sprinting, leaping, hopping, and change of direction in sports (Ramirez-Campillo et al., 2018, Meylan et al., 2010). Furthermore, unilateral tests such as unilateral countermovement jumps (Meylan et al., 2009, Pérez-Castilla et al., 2021), unilateral drop jumps (Millett et al., 2016), and horizontal hopping tests (McCubbine et al., 2018) are becoming increasingly prevalent in testing batteries. The aforementioned SSC tasks rely on larger knee and hip force contributions rather than ankle contributions compared to sub-maximal hopping (Xu et al., 2023, Farley and Morgenroth, 1999). During rebound tasks like sprinting, another parameter, stiffness may play a crucial role in explaining performance (Millett et al., 2016) given that it is associated with maximal sprint speed in boys (Chelly and Denis, 2001, Meyers et al., 2019) and explains a small portion of the variability during sprinting in boys (Meyers et al., 2016). Vertical stiffness during sprinting controls the vertical motion of the center of mass in response to an applied load (Farley and Morgenroth, 1999), leg stiffness describes the ratio of an applied force and the maximum compression of the leg, while joint stiffness describes the change in joint angle in response to a force at the joint (Ford et al., 2010). Although knee stiffness is higher in sprinting than ankle stiffness, especially with increasing speed, ankle stiffness is still quite high during sprinting (Arampatzis et al., 1999, Günther and Blickhan, 2002), while plantar flexor tendon stiffness has been reported to contribute to improved sprint performance in youth (Enomoto et al., 2019). Importantly, leg stiffness comprises both a vertical and a horizontal component during forward locomotion (Farley and Gonzalez, 1996, Meyers et al., 2019). This horizontal component is neglected in the calculation of leg stiffness during solely vertical movements

like vertical hopping but must be accounted for during horizontal movements like sprinting (Farley and Morgenroth, 1999, McMahon et al., 2012). Adequate levels of leg stiffness during sprinting may facilitate spring like applications of force onto the ground by limiting excessive vertical deformation of the stance leg and appropriate resistance to horizontal braking forces (Clark and Weyand, 2014, Brughelli and Cronin, 2008a). This results in maintenance of high sprint speeds that are manifested by improvements in sprint factors like step frequency and contact time (Farley and Gonzalez, 1996, Meyers et al., 2016). Given the prevalence of unilateral actions in sports and the role of leg stiffness in the control and coordination of the ground contact phase during fast SSC tasks, exploring leg stiffness during unilateral hopping tasks like sprinting is necessary. Assessing this relationship amongst varying maturity stages during sub-maximal hopping will help describe the natural development of stiffness in girls more appropriately.

Sprinting performance changes with age (Nagahara et al., 2019) and maturation in girls (Colyer et al., 2020). However, the degree to which stiffness explains sprinting performance in girls of differing maturity status is unknown. In the absence of leg stiffness measured during sprinting, investigations focusing on the relationship between leg stiffness during sub-maximal hopping and sprinting performance in girls could indirectly indicate how stiffness manifested in sub-maximal hopping, an ankle dominant task, may influence sprint speed in girls. Additional factors deserving investigation for their potential influence on sprinting performance in girls include growth and maturation related changes in anthropometric variables like leg length (LL), body mass (BM) and body fat percentage (BF%). Increases in fat mass throughout adolescence has been proposed as a factor that adversely affects the ability of girls to produce relative force during sprinting (Nagahara et al., 2019). Similarly, increases in body mass after age 12 have resulted in a plateau of relative vertical stiffness during sprinting in boys and girls (Schepens et al., 1998). Furthermore, height increases height have been shown to positively influence increases in speed in pre peak height velocity (PHV) boys (Meyers et al., 2016) and in girls under 12.7 years (Nagahara et al., 2019). However, the combined effect of these biologically relevant variables has not been assessed for their relationships with sprinting in girls (Colyer et al., 2020, Moeskops et al., 2021, Sudlow et al., 2024). Knowledge of these relationships will help explain sprint performance more thoroughly in girls.

There is an uncertainty surrounding the influence of BM, BF% and LL on sprinting in girls, and it is unclear how leg stiffness affects sprinting in girls. Moreover, there is little research concerning the difference in leg stiffness between maturity groups in girls, especially during single leg tasks. Therefore, the primary purpose of this study was to investigate the difference in the magnitude of leg stiffness between maturity groups while sub-maximally hopping unilaterally at 2.5 Hz. The second purpose was to investigate the degree to which leg stiffness measured during unilateral sub-maximal hopping and anthropometric variables explain sprint performance in girls using maturity status as a covariate. It was hypothesized that absolute leg stiffness and relative leg stiffness would be larger in the more mature groups compared to the less mature groups, with significant differences between mid-pubertal and pre to early pubertal groups for both stiffness conditions (Lloyd et al., 2011b, Lehnert et al., 2020, Laffaye et al., 2016). The secondary hypothesis was that 20-meter sprint time would be explained by a combination of absolute stiffness, relative stiffness and anthropometric variables related to maturation (Laffaye et al., 2016, Moeskops et al., 2020, Naughton et al., 2000).

6.2 METHODS

6.2.1 Participants

A total of 251 participants were recruited to participate in this study. Participants were recruited based on the following inclusion criteria: a) youth female between the ages of 7-15 years, b) participation in a sport involving impact from running, jumping, or fast stretch-shortening cycle (SSC) type movements, c) being free from major orthopedic injuries (e.g., sprains, fractures, and tears) for at least three months prior to the start of the study, d) being free from any pain which would limit safe participation, or the ability to attend both the familiarization session and data collection session. These criteria resulted in 52 participants being excluded from the study, leaving a total of 199 participants for analysis. The average hours of sport participation per week, as determined by self-reporting, was 8.80 hours. Participant details for each group are reported in Table 6.1. All participants and their parents/guardians were informed of the benefits and risks of being a part of this study and written parental consent and participant assent were obtained. All data collection procedures

were reviewed and approved by the Auckland University of Technology Ethics Committee (reference number 19/434) and the Ethics Committee of the Faculty of Physical Culture, Palacký University Olomouc (reference number: 15/2023). This study was conducted according to the declaration of Helsinki regarding the use of human participants.

6.2.2 Study procedures

This cross-sectional study involved two testing sessions, where the first day served as a familiarization session. The familiarization session occurred between one and seven days prior to the officially recorded testing session. Participants were asked to avoid any additional vigorous activity 24 hours prior to the testing sessions to reduce the effects of fatigue (Turner et al., 2015). Each testing session began with a structured warm-up routine designed to gradually increase intensity and specificity. The warm-up sequence began with basic movement exercises such as skipping, jogging, and shuffling, followed by dynamic stretches targeting key muscle groups including the calves, quadriceps, hamstrings, and adductors. The next portion of the warm-up consisted of vertical bilateral and unilateral sub-maximal hopping, followed by a series of single and triple horizontal jumps and hops, each increasing in intensity. During the final portion of the warm-up, participants completed three sprints at progressively higher intensities (60%, 90%, and 100% of maximal effort). Throughout the sessions, participants received consistent verbal encouragement from the researchers. All tests were conducted in the afternoon and were overseen by qualified researchers.

6.2.3 Testing protocols

6.2.3.1 Anthropometric and maturity measures

Participant standing height (cm) and seated height (cm) were measured using a portable stadiometer (Seca 213, Portable Stadiometer), following the method outlined by (Simmons, 2000). Leg length (LL) was determined by subtracting seated height from standing height. Body mass (BM) and body fat percentage (BF%) were assessed using a Bioelectric Impedance Analysis device, the Tanita® Sc-240 (Tanita Corporation, Tokyo, Japan). Maturity status was calculated using the percentage of predicted adult height method

(Khamis and Roche, 1994). Individuals with a percentage of predicted adult height percentage at the time of observation (PAH%) under 85% were classified as pre-pubertal (PRE), those with a percentage between 85% and 90% were considered in the early pubertal stage (EPUB). These maturity statuses were collapsed into one group named EPUBPRE (PAH% = $82.64 \pm 4.55\%$, $n = 60$). The biological distinction between these groups mainly revolved around the idea that EPUBPRE was not experiencing PHV, MPUB (PAH% = $93.43 \pm 1.42\%$, $n = 33$) were likely experiencing PHV and LPUB (PAH% = $97.83 \pm 1.33\%$, $n = 106$) were past PHV (Cumming et al., 2017, Meyers et al., 2016). Individuals with a percentage between 90% and 95% were classified as mid-pubertal (MPUB), and those with a percentage equal to or above 95% were classified as late pubertal (LPUB) (Cumming et al., 2017). Calculations were performed using a customized Microsoft Excel® 2015 worksheet (Towlson et al., 2020).

Table 6.1. Participant characteristics per maturity group

Variable	EPUBPRE (<i>n</i> = 60)	MPUB (<i>n</i> = 33)	LPUB (<i>n</i> = 106)
Age (years)	10.10 ± 1.22	12.38 ± 0.87	14.25 ± 0.93
Stature (cm)	140.69 ± 9.60	159.77 ± 5.47	166.42 ± 6.60
LL (cm)	68.79 ± 5.50	78.85 ± 3.77	81.54 ± 4.66
BM (kg)	34.81 ± 8.01	47.55 ± 6.50	57.88 ± 8.36
BF (%)	19.75 ± 6.94	20.22 ± 5.92	24.13 ± 5.51

EPUBPRE = early and pre-pubertal maturity status; MPUB = mid-pubertal status; LPUB = late pubertal maturity status; LL = leg length; BM = body mass; BF = body fat percentage

6.2.3.2 Sub-maximal hopping

Absolute and relative leg stiffness were assessed through unilateral sub-maximal hopping at 2.5 Hz on the dominant leg. The dominant leg was assessed by leg preference (stance leg) during kicking (Waxman et al., 2018). Contact time and flight time data were recorded in real-time during unilateral hopping at 2.5 Hz. A mobile contact mat (SmartJump; Fusion Sport, Brisbane, Australia) equipped with an electronic hub was used to quantify leg stiffness (Lloyd et al., 2009, Beerse and Wu, 2016). Each participant completed one trial of 20 consecutive hops cued by a frequency set by a digital metronome (Lloyd et al., 2011b). Participants were directed to maintain a hands-on-hips position, hop in place with legs extended, while keeping their gaze forward. This protocol was used to minimize the influence of arm and trunk movements (Lloyd et al., 2009). Three minutes of passive rest was provided between each hopping condition to ensure sufficient recovery.

6.2.3.3 20-meter sprint

Maximal sprint speed was measured over a 20-meter sprint (Moeskops et al., 2021) using a radar device (Stalker ATS II, Texas, USA) with a sampling rate of 47 Hz. The reliability of this device to measure sprint speed in youth female athletes has been previously established by Talukdar et al. (2021a), who observed coefficient of variation percentages of 3% and ICCs of 0.88 for the 20-meter sprint. The device was set at 94 cm above the ground, to attempt to align the device with the approximate height of the center of mass of the study population (Virmavirta and Isolehto, 2014, di Prampero et al., 2005). Participants were directed to assume a split stance starting position, with their preferred foot positioned just behind the starting line, located five meters ahead of the radar device (Talukdar et al., 2021a). They were instructed to get "down and ready", then remain "still like a statue" to encourage them to be motionless. Once motionless, the radar device was triggered on the attached laptop. The researcher then signalled, "go whenever you want," allowing participants to initiate the sprint at their own discretion. They were further instructed to start explosively using only forward movement. To ensure maximal effort throughout the entire 20-meter sprint, participants were instructed to run an additional two and a half meters beyond the finish line, which was marked by a pylon. Each participant completed three maximal sprints, with three minutes of passive recovery between each sprint.

6.2.4 Data analyses

6.2.4.1 Absolute and relative leg stiffness

Data were automatically uploaded to the Smartjump/Vald database online. Data were exported from the online database to an excel CSV file then converted to an xlsx file and saved. The contact time data were inspected for atypical hops. Atypical hops consisted of hops that exceeded 300 milliseconds (Sylvester et al., 2024). These atypical hops typically occurred if the participant lost their balance, misheard any start, or stop instructions, or made incomplete contact with the mat. In an overwhelming majority of cases, only one contact was removed. Contact time and flight time data were used to automatically calculate absolute leg stiffness using the Smartspeed/Vald software using the calculation method described by Dalleau et al. (2004). This method used the following equation to model the ground reaction force over time like a sine wave and determine absolute leg stiffness in kilonewtons per meter (kN/m). In Equation 1, M = body mass (kg), π = the half period of the sine wave, T_f = flight time (s), T_c = contact time (s), K_{leg} = leg stiffness (kN/m)

$$K_{leg} = [M * \pi (T_f + T_c)] / T_c^2 [(T_f + T_c / \pi) - (T_c / 4)]$$

[Equation 1]

The leg stiffness of each individual hopping contact was averaged to give a final leg stiffness value for each participant. Relative leg stiffness was calculated by multiplying absolute leg stiffness (kN/m) by the quotient of body mass (kg) and leg length (m) to provide a dimensionless value (De Ste Croix et al., 2017).

$$K_{leg} \times \left[\frac{L}{M} \right] = \text{Leg stiffness relative to leg length and body mass}$$

[Equation 2]

5.4.2 Sprint time and maximal velocity

Raw velocity-time data were collected continuously by the radar device from the onset of the sprint until it was manually stopped on the laptop by the researcher. The collection was facilitated by the Stalker ATS II software (Stalker ATS II, Texas, USA). This raw

instantaneous velocity data was automatically processed and stored in pre-selected computer files. These files were then imported into Matlab (R2021a) where a customized coding script modelled the raw instantaneous velocity data with a mono-exponential function to give horizontal velocity over time (Runacres et al., 2019). Horizontal velocity over time was integrated to a displacement value to be able to arrive at a distance over time relationship and ultimately determine a 20-meter sprint time for the three trials for each participant. The average of the three trials was used for analysis (Simperingham et al., 2019, Talukdar et al., 2021a).

6.3 STATISTICAL ANALYSES

Statistical analyses were completed within JASP [V.0.1.8.3]. Descriptive data are reported as means and standard deviation, where relevant.

6.3.1 Difference in leg stiffness across maturation

To investigate the effect of maturity status on the magnitude of absolute and relative leg stiffness (dimensionless), separate one-way analyses of variance (ANOVA) of between group effects were employed. Maturity groups, EPUBPRE, MPUB, LPUB, served as between-subject factors, while absolute and relative leg stiffness assessed during unilateral hopping at 2.5 Hz on the dominant leg, served as the dependent variables. The data were examined to confirm parametric assumptions such as, normality of the dependent variable for each group using the Shapiro-Wilk test of normality (Razali and Wah, 2011), a Quantile-quantile (QQ) plot of the standardized residuals (Harrison et al., 2018), and finally, homogeneity of variance using Levene's test of equality of variances. Initially, there were normality and homogeneity of variance violations for the absolute and relative leg stiffness data. Data were log-transformed to reduce the normality issues and significant outliers were removed from the analysis (West, 2022, Curran-Everett, 2018). Bonferroni post hoc tests were employed to identify the origin of the differences between maturity groups. Lastly, Hedges' *g* effect sizes with 95% confidence intervals (CI) were reported to quantify the magnitude of differences between maturity groups using a customized spreadsheet (Cambridge University press & Assessment, 2024). Interpretation of the magnitude of Hedges' *g* were based on the following

thresholds: trivial 0.00–0.19, small 0.20–0.49, moderate 0.50–0.79, and large ≥ 0.80 (Cohen, 1988). Statistical significance was set at $p < 0.05$. To determine sample size, a power analysis was performed using G*Power version 3.1.9.7 (Faul et al., 2007). Statistical significance was set at $\alpha = 0.05$, power was set at $1 - \beta = 0.80$, and the total number of groups set at three. Although a large effect may be expected due to age and maturation for absolute leg stiffness during sub-maximal hopping, a small effect size ($d = 0.4$) was considered for the one-way ANOVA due to considerations for relative leg stiffness (Lloyd et al., 2011b). Under these conditions, the required sample size was 66 participants. With 199 participants, this requirement was satisfied.

6.3.2 Contribution of leg stiffness to sprint performance

Multiple linear regression was employed to explore the extent to which measures of leg stiffness and anthropometric variables explained 20-meter sprint time in girls. This form of analysis can incorporate multiple independent variables while determining the association with the dependent variable. This allows for a more comprehensive understanding of the various factors that contribute to a given outcome (Laerd, 2018). Absolute and relative leg stiffness measured on the dominant leg during sub-maximal hopping at 2.5 Hz and biologically relevant anthropometric variables such as body mass (Lloyd et al., 2011a), leg length (Lloyd et al., 2009, Moeskops et al., 2021), and body fat percentage (Cliff et al., 2012) served as continuous independent variables, with maturity status based on PAH% (EPUBPRE, MPUB, LPUB) served as a covariate. The multiple linear regression also used maturity status based on PAH%, as a categorical independent variable to determine the presence of a difference in 20-meter sprint time between maturity groups.

Normality and independence of residuals were confirmed by examining the QQ plot, and Durbin-Watson statistic, respectively. Collective and independent linearity of the dependent and independent variables were confirmed by visually inspecting a scatterplot of the predicted vs standardized residuals and partial regression plots respectively (Laerd, 2018). Homogeneity of variance was confirmed by visually inspecting the spread of the predicted against standardized residuals (Laerd, 2018). Lack of multicollinearity was confirmed by

verifying if the variance inflation factor for all independent variables was below 10 (Laerd, 2018). The data were assessed for unusual points such as outliers (Casewise diagnostics), leverage points (Diagnostics) and influential points (Cook's distance). Two cases (case 24, 125) were identified as unusual with standardized residuals above the threshold value of three. A sensitivity analysis was performed, revealing very minimal effects of the unusual points. Therefore, they were kept in the model (Laerd, 2018, Zuur et al., 2010).

Regression model fit was judged based on the significance of the model F statistic, the magnitude of the adjusted R^2 value, and the normality and spread of the residuals (Laerd, 2018). To assess the influence of each independent variable to the variation of the dependent variable, standardized regression coefficients with associated p values and 95% confidence intervals were examined. The effect of maturity status on 20-meter sprint time was interpreted based on the unstandardized coefficients. To assess the strength and direction of the unique relationships between individual predictors and the dependent variables while controlling for the effects of another independent variables, the part and partial correlation plots were interpreted (Laerd, 2018). The level of statistical significance was set at $p < 0.05$ for the raw and standardized regression coefficients. The interpretation of the part and partial correlations was based on the following criteria: trivial 0.00–0.09, small 0.10–0.29, medium 0.30–0.49, and large ≥ 0.50 (Cohen, 1988).

6.4 RESULTS

6.4.1 Differences in leg stiffness between maturity group

One-way ANOVA data including the mean, SD of absolute and relative leg stiffness for each maturity group along with the percentage mean difference with 95% confidence intervals, effect size with 95% confidence intervals, significance level for all between group data, are summarized in Table 6.2. Group means are presented in Figure 6.1 A and 6.1 B. Significant between group (significant F) differences were revealed for absolute leg stiffness ($p < 0.001$), and relative leg stiffness ($p = 0.02$). ANOVA post hoc tests revealed large significant differences for absolute leg stiffness between all groups: EPUBPRE and LPUB ($g = 2.55$, 95% CI = 2.13, 2.97), EPUBPRE and MPUB ($g = 1.27$, 95% CI = 0.81, 1.73), and MPUB

and LPUB ($g = 1.27$, 95% CI = 0.85, 1.69). Meanwhile, a significant and small difference for relative leg stiffness was only observed between EPUBPRE and LPUB ($g = 0.48$, 95% CI = 0.16, 0.8).

Table 6.2. Maturity group differences in leg stiffness

Variable	Maturity Group Differences								
	EPUBPRE Mean + SD	MPUB Mean + SD	LPUB Mean + SD	% difference (95% CI)	EPUBPRE - -MPUB ES (95% CI)	% difference (95% CI)	MPUB - LPUB ES (95% CI)	% difference (95% CI)	EPUBPRE - LPUB ES (95% CI)
Kleg 2.5 (kN/m)	12.58 ± 2.03	15.76 ± 2.27	18.87 ± 2.68	25.23 (24.97, 25.50)	1.27 [◇] (0.81, 1.73)	19.76 (19.51, 20.01)	1.27 [◇] (0.85, 1.69)	49.98 (49.84, 50.12)	2.55 [◇] (2.13, 2.97)
RelKleg 2.5 (kN/m)	25.33 ± 2.77	26.31 ± 3.90	26.70 ± 2.93	3.87 (3.52, 4.22)	0.29 (0.14, 0.71)	1.49 (1.17, 1.81)	0.16 (0.24, 0.55)	5.41 (5.22, 5.60)	0.48* (0.16, 0.80)

EPUBPRE = combined EPUB (Early pubertal girls) and PRE (pre-pubertal girls); MPUB = mid-pubertal girls; LPUB = late pubertal girls; SD = standard deviation; ES = effect size (Hedges' *g*); CI = confidence interval; Kleg = absolute leg stiffness; RelKleg = relative leg stiffness; kN/m = kilonewtons per meter.

* = significant difference ($p < 0.05$).

◇ = significant difference ($p < 0.01$).

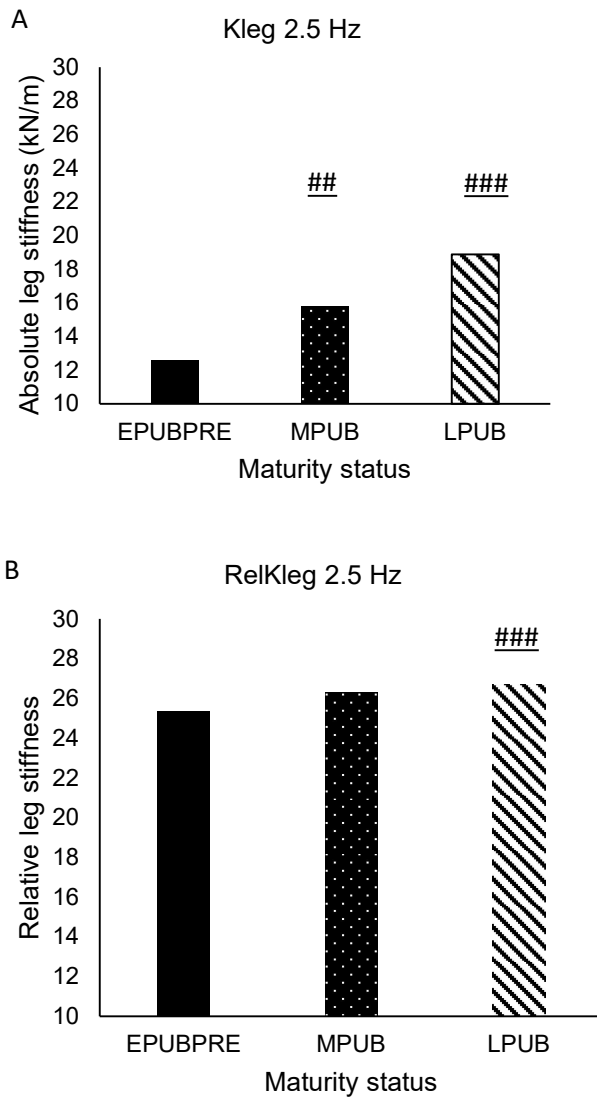


Figure 6.1. Maturity group differences in leg stiffness- Absolute leg stiffness (A), Relative leg stiffness (B). Kleg = absolute leg stiffness; RelKleg = relative leg stiffness; EPUBPRE = combined pre and early pubertal girls ($\bar{X} \pm SD = 12.58 \pm 2.03$); MPUB = mid-pubertal girls ($\bar{X} \pm SD = 15.76 \pm 2.27$); LPUB = late pubertal girls ($\bar{X} \pm SD = 18.87 \pm 2.68$); kN/m = kilo newtons per meter.

= significant difference from MPUB and EPUBPRE

= significant difference from LPUB and EPUBPRE

= significant difference from EPUBPRE

6.4.2 Contribution of leg stiffness and anthropometric variables to sprint performance

Standard multiple regression analysis of 20-meter speed including all beta coefficients with 95% confidence intervals, and p-values are presented in Table 6.3. The regression analysis revealed a significant F value ($F = 27.432, p < 0.001$), indicating a strong overall relationship between the independent variables and dependent variable. The residuals exhibited a normal and appropriate spread. The adjusted R^2 value was 0.484 ($p < 0.001$), indicating that absolute leg stiffness, relative leg stiffness, LL, BM, BF%, collectively explained 48.4% of the variance in 20-meter sprint time. Significant standardized coefficients were noted for absolute and relative leg stiffness, LL, BM, BF%, indicating significant change in 20-meter sprint time with a change in these variables. Specifically, an increase in LL was associated with a -0.019 s decrease in 20m sprint time, while increases in BM and BF% were associated with an increased sprint time of 0.022 s and 0.03 s, respectively. The part and partial correlations between each independent variable and 20m sprint time, while controlling for other independent variables is presented in Table 6.4 and Figures 6.2-6.6. Regarding maturity status, LPUB status reflects a -0.128 s (95% CI = -0.279, 0.023), 20-meter time difference compared to EPUBPRE, while MPUB status reflects a -0.044 s (95% CI = -0.181, 0.093) 20-meter time difference compared to EPUBPRE. These differences were not significant.

Table 6.3. Unstandardized, standardized coefficients with 95% confidence intervals, t-values, p-values, part, and partial correlations

	Unstan.	SE	Stand.	t	p	95% CI		Correlation	
						Lower	Upper	Partial	Part
(Intercept)	3.79	0.71		5.31	< 0.001	2.39	5.20		
Kleg 2.5 (kN/m)	-4.54	0.97	-1.38	-4.67	< 0.001	-6.46	-2.62	-0.32	-0.24
RelKleg_2.5 (kN/m)	3.98	1.0	0.61	3.95	< 0.001	1.99	5.97	0.27	0.20
LL (cm)	-0.02	0.01	-0.43	-3.07	< 0.01	-0.03	-0.01	-0.22	-0.16
BM (kg)	0.02	0.01	0.87	2.61	0.01	0.01	0.04	0.19	0.13
BF (%)	0.03	0.01	0.59	4.70	< 0.001	0.02	0.04	0.32	0.24
MatStatus (LPUB)	-0.13	0.08		-1.67	0.1	-0.28	0.02	0.14	0.10
MatStatus (MPUB)	-0.04	0.07		-0.63	0.53	-0.18	0.09		

Kleg = absolute leg stiffness; RelKleg = relative leg stiffness; LL = leg length; BM = body mass; BF = body fat; Matstatus = Maturity status; CI = confidence interval; kN/m = kilo newtons per meter; Unstan. = Unstandardized; Stan = Standardized.

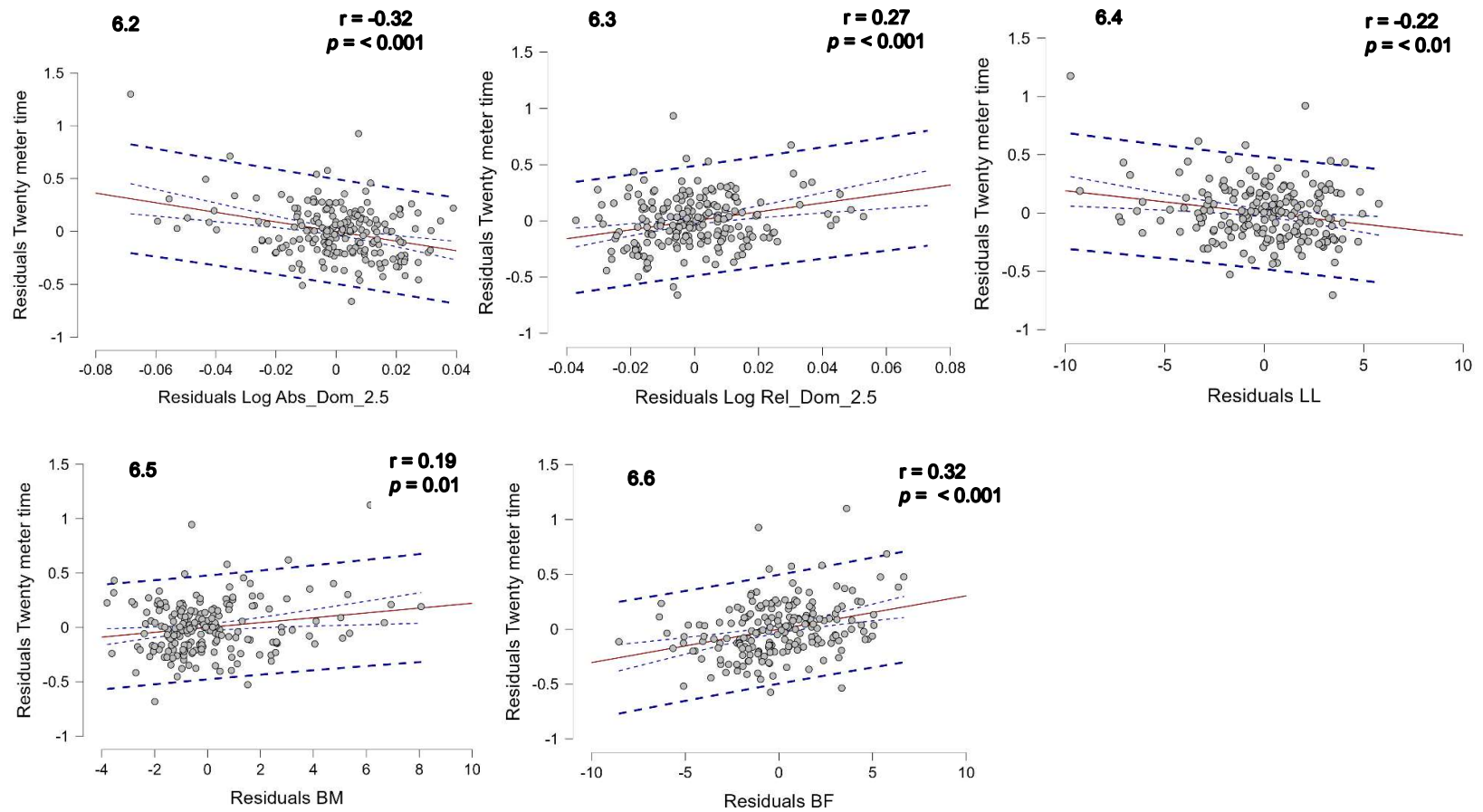


Figure 6.2-6.6. 20m sprint time partial correlations (log)

6.2 = absolute leg stiffness at 2.5 Hz; 6.3 = relative leg stiffness at 2.5 Hz; 6.4 = leg length; 6.5 = body mass; 6.6 = body fat%

BM = Body mass; BF = Body fat %; LL = leg length; Dashed lines immediately adjacent to regression line denote a 95% confidence interval.

6.5 DISCUSSION

This study examined absolute and relative leg stiffness differences during unilateral sub-maximal hopping among girls of varying maturity status. The findings demonstrated a significant linear increase in absolute and relative leg stiffness according to maturity status, with the distinction being that relative leg stiffness only differed significantly between late pubertal (LPUB) girls and the least mature group of girls (EPUBPRE). Moreover, 48.4% of variability in 20-meter sprint times were explained by absolute and relative leg stiffness, along with the biologically relevant anthropometric variables LL, BM, and BF. This study was the first to explore the differences in absolute and relative leg stiffness attributed to maturity status in young girls and to investigate the contribution of leg stiffness and anthropometric variables to sprinting performance in young girls.

6.5.1 Differences in absolute leg stiffness between maturity groups

Absolute leg stiffness differences between EPUBPRE and MPUB, and between MPUB and LPUB, were large and similar in magnitude for unilateral sub-maximal hopping at 2.5 Hz (Table 6.2). Underlying mechanisms that may explain this enhanced ability in more mature girls include, enhanced structural factors like tendon CSA or enhanced neuromuscular factors like improved muscle preactivation (Christoforidou et al., 2017, Lazaridis et al., 2010), improved stretch-reflex contribution (Lloyd et al., 2012a, Oliver and Smith, 2010), and decreased antagonist muscle coactivation (Radnor et al., 2017, Oliver and Smith, 2010, Lazaridis et al., 2010). These factors augment the ability to create a “stiff” response strategy. A stiffer response strategy encourages spring-like force applications (Radnor et al., 2021, Laffaye et al., 2016, Pedley et al., 2021), greater energy efficiency (Beerse and Wu, 2022), resulting in more effective coordination and control of the ground contact phase and a more effective rebound off the ground during sub-maximal hopping (Waxman et al., 2018, Pedley et al., 2021). The large and significant differences in absolute leg stiffness may suggest that maturity is a powerful driver of leg stiffness development, and it may highlight the differences in body mass and leg length that exist for more mature girls compared to less mature girls. Although speculative, the differences in absolute leg stiffness may also suggest the need to continually develop leg stiffness throughout childhood and adolescence to offset

the increases in body mass and leg length to maintain “stiff” ground contact strategies during hopping.

The linear development trend in absolute leg stiffness observed among the maturity groups in this study aligns with the findings of Chalatzoglidis et al. (2021), which documented similar development in Achilles tendon stiffness in both athletic and non-athletic girls and boys. They showed a linear and non-linear increase in Achilles tendon stiffness for athletic and non-athletic girls and boys respectively from 18 months before PHV until 12 months after PHV. Additionally, athletes exhibited a higher rate of increase in Achilles tendon stiffness compared to non-athletes. These findings, along with those of the current study, suggest that sport-related loading may influence musculoskeletal stiffness.

Previous research shows a non-linear increase in absolute leg stiffness with age or maturity during sub-maximal and maximal hopping in girls (Lehnert et al., 2020, Laffaye et al., 2016). However, disparities may exist in the development of absolute leg stiffness measured during these two tasks, possibly due to a larger reliance on muscle excursions during maximal hopping (Komi and Gollhofer, 1997, Farley et al., 1991). Comparatively, sub-maximal hopping relies more on the more efficient elastic properties of tendons, which may enhance the reversal of muscle action (eccentric to concentric) during fast-SSC tasks (Lloyd et al., 2009, Farley et al., 1991, Komi and Gollhofer, 1997, Maloney and Fletcher, 2018). Ultimately, these contributions facilitate shorter ground contact times, more spring-like action during sub-maximal hopping, and highlight the importance of considering the measurement task when evaluating absolute leg stiffness development in girls (Lloyd et al., 2009, Lloyd et al., 2012a).

It is also important to account for the maturity estimation method and study design when examining leg stiffness development in girls. For example, the current study demonstrated linear differences in absolute leg stiffness for maturity groups at 82.64% (EPUBPRE), 93.43% (MPUB) and 97.83% (LPUB) of predicted adult height percentage. Meanwhile their maturity offset was -1.7 (EPUBPRE), 0.54 (MPUB), and 2.03 (LPUB) years from PHV. The

participants' maturity status largely fell outside periods typically associated with declines in absolute leg stiffness. For example, a maturity offset of -1.7 years precedes the reported decline period around -1 to +1 years relative to PHV (Lloyd et al., 2011b). Furthermore, a maturity offset of 2.03 years in the current study, occurs after the decline period previously depicted from 0.9 to 1.7 years after PHV in girls (Lehnert et al., 2020) and 1.69 years after PHV in boys (De Ste Croix et al., 2021). This may be a consequence of the cross-sectional design in the current study. Cross-sectional designs assess physical qualities and maturation at a specific point in time, unlike longitudinal studies that track changes over time (Lehnert et al., 2020, De Ste Croix et al., 2021). Overall, disparities in absolute leg stiffness development may exist according to sex, athletic status/background, measurement task, type of stiffness, statistical approach, and the maturation estimation method. This dichotomy presents some complexities in accurately describing maturity-related absolute leg stiffness development.

6.5.2 Differences in relative leg stiffness between maturity groups

Relative leg stiffness differences were small and significant between EPUBPRE and LPUB, but non-significant between EPUBPRE and MPUB and between MPUB and LPUB. Additionally, the difference nearly doubled in magnitude from EPUBPRE to MPUB compared to the difference between MPUB to LPUB despite the non-significance. These findings resemble those of Lloyd et al. (2011b), who reported differing age-related development trends in relative leg stiffness between child and adolescent boys during bilateral sub-maximal hopping. Specifically, there was a sharp increase during childhood, followed by a decline between age 10.86 to 12.59 years, then a plateau throughout adolescence. A plateau in relative leg stiffness was also demonstrated by Laffaye et al. (2016) during maximal hopping in adolescent girls, whereas a significant decline has been observed in adolescent boys over a two-year period, and in adolescent girls during bilateral sub-maximal hopping (De Ste Croix et al., 2021, Lehnert et al., 2020). It has been suggested that relative leg stiffness development could be sensitive to increases in fat mass in girls, which tends to decrease relative force production (Colyer et al., 2020, Pedley et al., 2021). The higher relative force in children compared to adults at slow sub-maximal hopping frequencies suggests a potential adolescent-related decrease in relative force measures (Beerse and Wu,

2016). Nonetheless, the discovery of higher leg stiffness relative to body mass and leg length, in more mature girls suggests higher proficiency in size-independent factors. Factors like augmented muscle preactivation, enhanced contribution of the stretch-reflex, diminished antagonist co-contraction, and enhanced intermuscular coordination may improve the execution of a “stiff” ground contact strategy during fast-SSC tasks like unilateral hopping (Radnor et al., 2017, Tumkur Anil Kumar et al., 2021, Laffaye et al., 2016, Sudlow et al., 2024). However, significant declines in relative leg stiffness for 13–16-year-olds during sub-maximal hopping (Lehnert et al., 2020, De Ste Croix et al., 2021), and a plateau during maximal hopping suggest similar factors affecting both absolute and relative leg stiffness. Relative leg stiffness development is influenced by various factors including sex, athletic background, measurement task, type of stiffness, study design, and maturation estimation method. To gain a clearer understanding of relative leg stiffness in girls, it is advisable to compare measurement methods, athletic backgrounds, and maturation estimation methods.

6.5.3 Contribution of leg stiffness and anthropometric variables to sprint performance

The regression analysis in this study was able to establish collectively that absolute and relative leg stiffness, body mass, leg length and body fat percentage explained 48.4% of the variance in 20-meter sprint time. These findings highlight the importance of considering a combination of anthropometric factors and leg stiffness when investigating determinants of sprint performance in young girls. Absolute and relative leg stiffness emerged as significant explanatory variables of 20-meter sprint time. This result emphasizes the need to limit excessive vertical leg compression during sprinting to promote spring-like ground contacts for efficient elastic energy storage and reutilization (Clark and Weyand, 2014, Farley and Gonzalez, 1996). These factors aid in effective ground force application, propelling the body during sprinting, regardless of body size or composition (Clark and Weyand, 2014, Meyers et al., 2019, Schepens et al., 1998).

The partial correlation analysis for absolute leg stiffness indicated that, while controlling for the effects of other independent variables on both absolute leg stiffness and 20-meter sprint

time, a 1 SD increase in absolute leg stiffness was associated with a -1.38 SD decrease in sprint time. The partial correlation coefficient ($r = -0.32$) reflects the strength of this relationship, controlling for the effect of other predictors. Meanwhile, the part correlation ($r = -0.24$) indicates that absolute leg stiffness uniquely explains 5.76% of the variance in 20-meter sprint time (Hoyt et al., 2008). Similarly, relative leg stiffness uniquely explained 4%, leg length explained 2.56%, body mass explained 1.69%, and body fat percentage explained 5.76% of the variance in sprint time. Caution is advised in interpreting these results. While these variables are significant contributors to the model, the overlapping confidence intervals in the partial regression plots suggest uncertainty in their unique contributions to sprint performance. This may indicate that these variables are interrelated and should be considered collectively rather than in isolation when evaluating their influence on 20-meter sprint performance in young female athletes.

Body mass was revealed as a significant explanatory variable for 20-meter sprint time. While increases in body size are linked to enhanced force production (Sudlow et al., 2024), excessive body mass can increase inertial demands during sprinting. For example, Moeskops et al. (2021) revealed peak momentum (velocity x mass) as an influential factor in girls' sprint speed. They suggested that growth and maturation-related increases in body mass will increase moment of inertia, thus requiring higher amounts of momentum to move their bodies quickly. Leg length also emerged as a significant explanatory variable of 20-meter sprint time, corroborating previous research highlighting its importance in locomotor performance (Meyers et al., 2016). Longer limbs afford step length advantages, facilitating greater ground coverage per step and leading to faster sprint times (Meyers et al., 2016, Nagahara et al., 2019). Finally, the significant coefficient for body fat percentage indicates the importance of considering body fat alongside other anthropometric and stiffness factors while assessing sprint performance in young girls. It has been previously suggested that maturation-related increases in body fat can impair relative force production in girls (Nagahara 2019; Colyer 2020). Further investigations are required which explore the impact of fat increases on sprinting in young girls.

6.6 LIMITATIONS

There were a few limitations to be considered for the current study. *Firstly*, it is acknowledged that maturity status represents the current state of maturation at the time of measurement and thus, is able to show a general trend of development rather than the changes that occur over time like in a longitudinal study (Lloyd et al., 2014b, Cumming et al., 2017). However, this method of maturity estimation does carry a low amount of error compared to other non-invasive methods (Parr et al., 2020). *Secondly*, this study did not describe the difference in leg stiffness development for unilateral compared to bilateral hopping at the same frequency. This study did however provide valuable insights into how leg stiffness differs between girls of varying maturity status while hopping unilaterally. Unilateral differences according to maturity status have not previously been investigated in girls. *Thirdly*, the reliance on a contact mat prevents direct measurement of force-time variables that underpin leg stiffness mediated fast-SSC performance (Moeskops et al., 2020). The sine function used to model maximal force in the leg stiffness equation, is less precise than a direct measurement of force (Lloyd et al., 2009). However, the method used to model force is valid and reliable in youth hopping on a contact mat (Lloyd et al., 2009). Additionally, the portability and cost of a contact mat, provides users with a practical option to measure stiffness qualities.

6.7 CONCLUSION, PRACTICAL RECOMMENDATIONS

This study was able to provide insight into the maturity related development of absolute and relative leg stiffness during unilateral sub-maximal hopping. Absolute leg stiffness differed significantly between all maturity groups, while relative leg stiffness only differed significantly between the least and most mature groups. These findings reflect the importance of evaluating the natural progression of a physical property. The large differences between maturity groups reflect a substantial influence of maturity status on leg stiffness development. Additionally, the examination of absolute and relative leg stiffness indirectly recognizes the variety of mechanisms that may contribute to leg stiffness development in young girls. Specifically, anthropometric factors (e.g., body mass, leg length) for absolute leg stiffness and neuromuscular factors (e.g., extensor muscle activity) for relative leg stiffness. This study was also able to show how absolute and relative leg stiffness, together with body mass, leg

length, and body fat percentage, explained 48.4% of sprint time variability. Leg stiffness as an explanatory variable of sprint time highlights the need to increase the resistance to leg compression during sprinting for efficient propulsion. These findings also emphasize the interplay between musculoskeletal properties and body size and composition in determining sprint performance in young girls. While it is acknowledged that activity-related loading may influence leg stiffness, maturity is likely to most substantial source of adaptation for absolute leg stiffness. However, considering the decline in relative force production with rapid fat mass increases in girls with puberty, it is recommended for girls to engage in training that may enhance relative forms of leg stiffness. Actions that increase relative force production (e.g., strength training) and methods that address neuromuscular factors (e.g., plyometric training), may encourage the development of relative leg stiffness beyond that of normal growth and maturation.

CHAPTER 7. THE EFFECTS OF LINEAR SPRINT TRAINING COMPARED TO PLYOMETRIC TRAINING ON LEG STIFFNESS IN YOUTH FEMALE ATHLETES

7.0 PRELUDE

Chapter 5 and 6 reported maturity-related differences in measures of global stiffness during sprinting and sub-maximal hopping, respectively. Chapter 6 identified that during unilateral vertical sub-maximal hopping, absolute leg stiffness differed significantly across all maturity groups, while relative leg stiffness only differed significantly between the least and most mature groups. Furthermore, together with body mass, leg length, and body fat percentage, leg stiffness explained 48.4% of sprint time variability. Body mass and body fat percentage may impact sprint performance by increasing inertia, requiring higher force and momentum to accelerate the body and sprint quickly. Higher leg stiffness of more mature girls during sub-maximal hopping may minimize leg compression during sprinting to enhance propulsion efficiency. Data from Chapters 5 and 6 allowed for the identification of the expected magnitude of difference in global measures of stiffness according to maturity status. To induce stiffness adaptations above what occurs naturally, training is recommended that targets either the relevant morphological stiffness mechanisms (e.g., tendon cross-sectional area) or the relevant neuromuscular stiffness mechanisms (e.g., stretch-reflex contribution). Two such training methods that target the neuromuscular stiffness mechanisms and can be conducted with girls of all ages without any resource constraints are plyometric and sprint training. However, the expected training-related change is unknown for plyometric and sprint training alone among young girls. Therefore, this study aims to compare the effects of plyometric and sprint training on leg stiffness relative to a control group.

7.1 INTRODUCTION

Leg stiffness is a physical property that helps regulate the stretch-shortening cycle (SSC) during the ground contact phase of rebound tasks like sprinting and hopping. It limits excessive leg compression in response to applied forces (Millett et al., 2016, De Ste Croix et al., 2021). Leg stiffness can improve due to growth and maturation-related factors (Meyers

et al., 2016) and physical training (Lloyd et al., 2011c, De Ste Croix et al., 2018), including increases in body mass and muscular strength (peak force capacity) which stimulate enhancements in muscle and tendon dimensional properties such as cross-sectional area (CSA) (Vaugh et al., 2012). They also include improvements in tendon material properties like Young's Modulus, which describes the stiffness of the intrinsic material or collagen microstructure (Bailey and Paul, 1999, Huda, 2022). However, when considering training-related adaptations throughout childhood and adolescence, the effectiveness of training interventions relies on being able to induce adaptations above and beyond natural increases in stiffness (Lloyd et al., 2012c, Moeskops et al., 2022a). For this purpose, including control group data in research designs to reduce bias is essential when conducting training intervention studies in youth populations (Lloyd et al., 2015a, Cohen, 1988).

Training-related stiffness improvements have been accomplished with training that targets the control mechanisms of SSC function (Radnor et al., 2017, Millett et al., 2018). These mechanisms include neuromuscular recruitment and activation prior to and early on in the ground contact phase, increased stretch-reflex contribution and optimization of elastic energy storage and reutilization (Oliver and Smith, 2010). Training methods that target SSC mechanisms include plyometric training and running/sprint training (Ramirez-Campillo et al., 2023a, Moran et al., 2017a). Only one study in boys has included an exploration into the effects of running training on leg stiffness (Uthoff et al., 2018). These researchers reported significant increases in leg stiffness during sub-maximal hopping following run-based training. Additionally, research on healthy people of all ages has involved reports of trivial to small stiffness effect sizes following plyometric training (Moran et al., 2023). Stiffness adaptations were also more favorable for less experienced individuals and programs lasting more than seven weeks, with a training frequency of one to two days per week and lower training volume (under 250 jumps per week)-(Moran et al., 2023). However, non-significant differences between post-PHV and pre-PHV youth have been reported regarding the effect of plyometric training on explosive outcomes like countermovement jump height, reactive strength index, horizontal jump distance, but with no data on vertical hopping tasks and stiffness measures (Ramirez-Campillo et al., 2023a). This finding indicates the importance of considering the effect of maturity status on explosive athletic tasks and training parameters in youth.

Training methods that have targeted some form of global stiffness (vertical, leg, joint) in girls have included resistance training (İnce, 2019), plyometric training (Katsikari et al., 2020, Sylvester et al., 2024) and various combinations of muscular endurance, muscular strength, plyometrics, speed, movement competency and stabilization training (Moeskops et al., 2022a, Moeskops et al., 2018a, De Ste Croix et al., 2018). While these methods have proven effective for enhancing leg stiffness in mid-PHV and post-PHV girls (De Ste Croix et al., 2018), results were less clear for pre-pubertal girls (Moeskops et al., 2022a, Moeskops et al., 2018a). However, comprehension of the precise adaptation mechanisms becomes challenging when combining various training methods, such as integrating plyometric and resistance training. Furthermore, methods that require resistance training equipment may present resource constraints for some practitioners. Conversely, plyometric and sprint training methods provide fewer resource constraints, and to date, have not been investigated to the same extent in girls (Ramirez-Campillo et al., 2023a). Therefore, further investigation into the potential leg stiffness adaptations of plyometric and sprint training in girls is warranted (Moran et al., 2023, Gevat et al., 2012).

Sprinting and plyometric training are similar in that they both involve high rates of force development, power and impulse (Ramirez-Campillo et al., 2023a), which facilitate the body being projected upwards and forwards (Clark and Weyand, 2014, Moir et al., 2018, Oliver et al., 2013). They also both involve applying force against the ground in a reactive manner, necessitating muscle preactivation, stretch-reflex contribution and thus a “stiff” strategy to control and coordinate the SSC (Oliver and Smith, 2010). However, there are also notable differences between sprinting and plyometric exercises. *Firstly*, the magnitude of key sub-maximal hopping determinants (e.g., leg stiffness, center of mass displacement, peak vertical ground reaction force [VGRF] and contact time), have been shown to exceed those determinants during sprinting (Millett et al., 2018). Furthermore, the center of mass displacement and contact times during vertical and horizontal drop jumps exceed those of running. Horizontal drop jumps involve a countermovement jump onto a force plate, immediately followed by a maximal jump for distance (Stålbom et al., 2007). Running has a higher normalized VGRF (%body weight) compared to horizontal drop jumping (Millett et

al., 2016), whereas vertical hopping VGRF (%body weight) exceeds that of sprinting (Millett et al., 2018). Finally, step-averaged vertical forces during sprinting may reach ~13-18 N/kg with contact times (T_c) between 0.14-0.18 s (Colyer et al., 2020). Conversely, vertical drop jumping from 30 cm may produce a VGRF ~30 N/kg and $T_c \sim 0.214$ s in girls (Moeskops et al., 2020). Therefore, these two methods present differences in kinetic and spatiotemporal variables that make comparing both methods worth exploring. The combined findings indicate that plyometric training may serve as a more appropriate method to elicit leg stiffness adaptations; however, this has not been examined empirically.

To limit the potential differences due to force orientation between plyometric and sprint training, it is possible to engage in horizontally oriented plyometric exercises (e.g., forwards hopping, bounding). However, horizontally oriented plyometric and sprint training interventions have not been conducted to the same extent as vertically oriented plyometric interventions in girls (Ramirez-Campillo et al., 2023a). Therefore, it is uncertain if horizontally oriented plyometric training or sprint training is more effective for girls attempting to improve leg stiffness, explosive jumping and hopping ability (Myer et al., 2005, Noyes and Barber-Westin, 2015, Bogdanis et al., 2019, Moran et al., 2018c, Ramirez-Campillo et al., 2023a). The primary purpose of this study was to compare the impact of linear sprint training versus horizontal plyometric training relative to a control group on measures of leg stiffness and horizontal jumping and hopping. The primary hypothesis proposed that plyometric training would improve measures of leg stiffness and horizontal jumping and hopping to a greater degree than sprint training relative to a control group.

7.2 METHODS

7.2.1 Participants

A total of 74 girls volunteered to participate in this study. Participants were recruited based on the following inclusion criteria: a) youth female athletes between 7-15 years of age; b) participation in a sport involving fast-SSC running or jumping movements; c) being free from major orthopedic injuries (e.g., sprains, fractures, and tears) for at least three months before the start of the study; d) being free from any pain which would limit safe participation. Based

on quasi-randomization, where a combination of randomization and samples of convenience were employed, participants were assigned to one of three groups (McCormick et al., 2016), plyometric training group (PTG) (age, 13.55 ± 1.35), a sprint training group (STG) (age, 11.52 ± 2.13) and a control group (CG) (age, 10.91 ± 2.35). The training groups were heterogenous in terms of their biological maturation which was based on predicted adult height percentage (PAH%) (Khamis and Roche, 1994). Specifically, the spread of data indicates that the CG is composed of prepubertal, early pubertal and mid-pubertal girls, the STG of all pubertal stages and the PTG of mid and late pubertal status. Specific participant details for each group are reported in Table 7.1. Leg dominance was determined by the stance leg during kicking (Waxman et al., 2018). The left leg represented the dominant leg for most participants. The groups were unequal in terms of number of participants, and there were significant group effects for maturity status ($p = 0.009$) and leg length ($p = 0.05$). Furthermore, since the data were collected in cohorts, it was considered clustered data, which might produce overly correlated observations (Monsalves et al., 2020). These differences and issues were accounted for using a linear mixed effects model (LMM), where maturation was controlled for when assessing the isolated effect of group and time and the interaction of group and time (Monsalves et al., 2020).

The PTG, STG and CG were composed of athletes who participated in multiple sports. Participants were required to participate in pre-testing and post-testing sessions for a given assessment and participate in at least 75% of the total training sessions to be considered for analysis (Lloyd et al., 2012c). Due to these criteria, 26 participants were excluded, leaving 48 participants for analysis. All participants and their parents/guardians were informed of the benefits and risks of participating in this study; written parental consent and participant assent were obtained before the study started. All data collection procedures were reviewed and approved by the Auckland University of Technology Ethics Committee (reference number 19/434) and the Ethics Committee of the Faculty of Physical Culture, Palacký University Olomouc (reference number: 15/2023). This study was conducted according to Helsinki's declaration regarding the use of human participants.

Table 7.1. Anthropometric characteristics per training group

Variable	<i>n</i> = 48	CG Mean + SD (<i>n</i> = 10)	PTG Mean + SD (<i>n</i> = 22)	D/f to CG (%)	STG Mean + SD (<i>n</i> = 16)	D/f to CG (%)
BM (kg)	Pre	40.06 ± 13.04	56.73 ± 10.79	41.60	43.35 ± 12.63	8.20
	Post	40.14 ± 13.01	57.86 ± 11.33*	44.10	44.27 ± 12.45*	10.30
Stature (cm)	Pre	146.01 ± 13.98	164.86 ± 7.49	12.90	153.36 ± 12.94	5.00
	Post	146.11 ± 14.01	165.36 ± 7.68*	13.20	154.16 ± 12.94*	5.50
LL (cm)	Pre	71.39 ± 6.77	80.92 ± 4.96 ^{gr}	13.40	75.26 ± 6.69	5.40
	Post	71.56 ± 6.81	81.16 ± 5.11	13.40	76.10 ± 6.89	6.30
BF%	Pre	19.60 ± 8.05	23.75 ± 6.09	21.20	19.91 ± 6.64	1.60
	Post	19.70 ± 7.94	23.75 ± 6.13	20.60	19.95 ± 6.77	1.30
PAH%	Pre	84.56 ± 7.64	96.49 ± 3.23 ^{gr}	14.10	88.79 ± 8.37	5.00
	Post	84.60 ± 7.64	96.88 ± 3.14	14.50	89.60 ± 7.45*	5.90

SD = standard deviation; PTG = plyometric training group; STG = sprint training group; D/f = raw difference; CG = control group; BM = body mass; LL = leg length; BF% = body fat percentage; %PAH = predicted adult height percentage; *n* = number of participants; gr = significant group effect; * = significant group by time interaction.

7.2.2 Study procedures

The quasi-experimental design of this study involved pre-testing, eight-weeks of plyometric and sprint training interventions twice a week, and post-testing. Participants attended a familiarization session one to seven days before the pre-testing and post-testing sessions. All testing sessions involved anthropometric measurements, vertical sub-maximal hopping tests, and horizontal jump and hop tests. Participants were asked to avoid any additional vigorous activity 24 hours before the testing sessions to reduce the effects of fatigue (Turner et al., 2015). All testing sessions commenced with a standardized warm-up, progressing from low to high intensity, simple and general, to complex and specific. The warm-up commenced with fundamental movement skills such as skipping, jogging, and shuffling, followed by dynamic stretching that targeted the calves, quadriceps, hamstrings, and adductor muscle groups. The ensuing portion of the warm-up required participants to perform vertical bilateral and unilateral sub-maximal hopping, a series of single and triple horizontal jumps and hops of progressive intensity and three sprints of progressive intensity (60% to 90% to 100% of maximal effort). Consistent verbal encouragement was employed for each participant during each trial throughout all sessions, and tests were performed at the same time of day by the same qualified researchers.

7.2.3 Testing protocols

7.2.3.1 Anthropometric and maturity measures

Participants' standing height (cm) and seated height (cm) were measured using a portable stadiometer (Seca 213, Portable Stadiometer) using the method outlined by Simmons (2000). Leg length (cm) was calculated by subtracting seated height from standing height. Body mass (kg) and body fat percentage (%) were quantified using a Bioelectric Impedance Analysis device (Tanita® Sc-240, Tanita Corporation, Tokyo, Japan). Maturity status was calculated using the predicted adult height percentage method (Khamis and Roche, 1994). In this method, a percentage of predicted adult stature under 85% of predicted adult stature is considered pre-pubertal (PRE). A percentage equal to and above 85% and below 90% is considered in the early pubertal stage (EPUB), whereas equal to and above 90% but below 95% is considered mid-pubertal (MPUB). A percentage equal to and above 95% is regarded

as the late pubertal stage (LPUB) (Cumming et al., 2017). Calculations were executed using a customized Microsoft Excel® 2015 worksheet (Towlson et al., 2020). Given the unevenness of the groups in terms of maturity status and participant numbers, the effect of maturity status was controlled using a linear mixed-effects model, which is outlined in section 3.0.

7.2.3.2 Sub-maximal hopping

Vertical bilateral and unilateral sub-maximal hopping were used to determine absolute and relative leg stiffness. Data were collected instantaneously while hopping bilaterally at 2.0 and 2.2 Hz on a mobile contact mat with an attached electronic hub (SmartJump. Fusion Sport, Brisbane, Australia). These sub-maximal hopping protocols have been shown to be reliable for girls hopping on a contact mat (Chapter 3 - under review). Similarly, data were collected while hopping unilaterally on the non-dominant and dominant legs, both at 2.5 and at 3.0 Hz (Lloyd et al., 2009, Beerse and Wu, 2016). Each participant completed one trial of 20 consecutive hops, cued by a frequency set by a digital metronome (Eiling et al., 2007). Participants were instructed to keep their hands on hips, jump and land on the same spot, land with legs extended and maintain their gaze forward to minimize the additive effect of the arms and trunk (Lloyd et al., 2009). Three minutes of passive rest were given between each hopping condition to ensure adequate recovery.

7.2.3.3 Horizontal jumping and hopping

Single and triple broad jump tests and single and triple broad hop tests were used to measure maximal horizontal jumping and hopping distance (cm). The broad jump tests were executed using a two-foot take-off and landing. However, the broad hop tests involved a one-leg take-off but a final landing on two feet (Rivera et al., 2023, Standing and Maulder, 2019). The reliability of hopping using this technique has been demonstrated in both less mature (pre-pubertal and early pubertal) and more mature girls (late pubertal) (CV < 10%, ICC > 0.9) (Chapter 4 - under review). Jump and hop distance was measured from the start line to the rearmost heel to the nearest 0.2 cm using a standard fiberglass tape measure over two trials. One-minute of recovery was given between trials, and two-minutes of recovery was given

between jump or hop type. Jump and hop attempts were disallowed if the participant shifted their foot position, put their hands on the ground upon landing, or if the free leg touched the ground before the final landing in a hop test.

7.2.3.3.1 Broad jumps

For the broad jump (BJ) and triple broad jump (TBJ) tests, participants started in a standing position with the toes of both feet behind the start line. The BJ and TBJ required the participant to start with a countermovement and perform a maximum horizontal jump once or thrice without pause, respectively (Ramirez-Campillo et al., 2015b, Hudgins et al., 2013).

7.2.3.3.2 Broad hops

Broad hop tests involved the single broad hop on the right leg (SBHR), single broad hop on the left leg (SBHL), triple broad hop on the right leg (TBHR) and triple broad hop on the left leg (TBHL). Participants started in a standing position with the toes of one foot behind the start line. For the SBHR and SBHL tests, participants executed a countermovement, followed by a maximal hop for distance, and a two-foot landing (Maulder and Cronin, 2005). The TBHR and TBHL tests required participants to perform three maximal consecutive hops for a distance without pausing, followed by a landing on two feet (Hammami et al., 2016, Turner and Jeffreys, 2010, Ramirez-Campillo et al., 2018).

7.2.4 Training programs

The training interventions lasted eight weeks, with two sessions per week on non-consecutive days, and were administered by a qualified and experienced strength and conditioning coach. Each session commenced with a five to seven-minute warm-up of problem-based movement activities (Radnor et al., 2020). These warm-up activities progressed from low to high intensity and simple to complex. Each session lasted between 35–45 minutes. Plyometric exercises and sprint coordination exercise progression involved increasing intensity (eccentric load) of a variety of movements (Lloyd et al., 2011c), followed by an increase in set volume and repetition volume (Talukdar et al., 2022, Chaouachi et al., 2014, Ramirez-

Campillo et al., 2023a, Moeskops et al., 2022a). Linear sprint exercises were always completed at maximal intensity; thus, they progressed based on volume (Gevat et al., 2012). All volume for all plyometric and sprint exercises was tracked by distance travelled (Ramirez-Campillo et al., 2023b). Exercise quality was carefully observed during each session to ensure proper execution and limit the risk of injury. For example, elements of proper jumping execution can include avoiding excessive movement laterally, maintaining an upright posture, and exploding up and over the ground (Johnson et al., 2011). Researchers routinely confirmed with the participants whether the exercises produced any pain; notably, no injuries occurred throughout the intervention. When the expected technical proficiency was not achieved, a regression of the exercise was administered as a teaching tool, but volume integrity was maintained. Participants from the experimental groups continued their involvement in their weekly sport-specific training in addition to the intervention, which included a combination of practices and games. Conversely, participants from the control group participated in their regular sport-specific activities but did not receive any formalized strength and conditioning.

7.2.4.1 Plyometric training program

The plyometric training program consisted of horizontally oriented plyometric exercises according to the loading classification of Lloyd et al. (2011c). Exercises were prescribed with the intention of targeting fast-SSC activity (i.e., ground contact times < 250 ms) and progressed using a three-level system, based on technical and physical competency similar to the structure of De Ste Croix et al. (2018). For example, skipping exercises progressed from rhythmic skipping (without emphasis on height) to skipping for height, and finally to skipping for both height and distance. Each exercise consisted of three to six sets, requiring participants to traverse 10–25 meters per set. Detailed information about the intervention can be found in Table 7.2.

Table 7.2. Plyometric training program

Category	Intensity	Technique progressions
MDJLC	2- Low	Bilateral jump, jump stick, Unilateral hop, hop stick
MDAH	3- Moderate	Travelling forwards, backwards, and laterally (Emphasize ankle dorsi-flexion)
Power skipping	3- Moderate	Skipping with rhythm - Skipping for height - Skipping for distance
Galloping	3- Moderate	Galloping with rhythm- Galloping for height- Galloping for distance
Broad jumping	2- Low	Broad jump with reset - Two “pump” broad jump with reset - Repeat broad jump
Horizontal hopping	4.5-Mod/High	Rhythm hops (100 Bpm) - Hop over cones - Hop for distance
Bounding	5- Mod/High	Diagonal bounding - Straight bounding (short) - Straight bounding (long)

MDJLC = multi-directional jump landing combination; MDAH = multi-directional ankle jumps; Mod = moderate; Bpm = beats per minute.

7.2.4.2 Sprint training program

The sprint training program was comprised of sprint coordination drills and race or chase-style linear sprinting. The race and chase elements were meant to increase participants' engagement and to encourage maximal intensity. To ensure proper technical execution, maintain time efficiency, and deliver proper verbal encouragement, participants were partnered with an approximate aged-matched partner to execute their sprints (Oliver et al., 2013). The sprint coordination drills chosen did not resemble the plyometric exercises (i.e., jumping, hopping, or leaping). The sprint coordination drills focused on targeting the coordinative structure of sprinting to promote fluent and reflexive movement while minimizing cognitive strain (Barillas et al., 2021). This concept involved coaching cues that focused on applying large and fluid downward leg movement and reciprocal arm movement, as the participant moved forward (Moir et al., 2018). Furthermore, the drills required the rhythmic swinging of the upper limbs from the shoulders. Drills were progressed using a three-level system, based on technical and physical competency (De Ste Croix et al., 2018). Participants completed the linear sprinting and sprint coordination drills over distances of 10–25 meters during three to six sets. Further details of the sprint training program are presented in Table 7.3.

Table 7.3. Sprint training program

Category	Technique progressions
Toe pulls	Legs only, toe pulls, toe pull + sprint
Mini hurdle high knees	Legs only, high knee, high knee + sprint
Free high knees	Legs only, high knee, high knee + sprint
Chase sprints	High start, leaning start, half-kneeling start, belly start
-Forward start	
Chase sprint	High start, athletic ready position start, half kneeling start, belly
-Sideways start	start
Relay race	High start, leaning start, half-kneeling start, belly start

7.2.5 Data analyses

The calculation of absolute leg stiffness using the method described by Dalleau et al. (2004) has been shown to be valid and reliable in youth (Lloyd et al., 2009). Absolute leg stiffness was calculated using the average stiffness of all contacts in a single trial, excluding atypical hops (Sylvester et al., 2024). Atypical hops generally exceeded 300 ms, where the participant may have lost their balance and/or made incomplete contact with the mat, or where participants misheard instructions and stopped for too long or lost rhythm. Relative leg stiffness was calculated by multiplying absolute leg stiffness by the quotient of body mass and leg length to provide a dimensionless value (De Ste Croix et al., 2017).

The average of both trials was used to determine absolute jump and hop distance and subsequently used for analysis (Myers et al., 2014). Relative horizontal jump and hop distance was calculated by dividing the average of both trials by participant leg length (Moeskops et al., 2021).

7.3 STATISTICAL ANALYSES

7.3.1 Linear mixed-effects model- time, group, maturity status, group x time

A linear mixed-effects model was employed to evaluate the impact of plyometric and linear sprint training on leg stiffness and jump and hop distance relative to a control group. This model was used due to its flexibility and robustness in accommodating the repeated measures design across groups while accounting for error from individual participants, its ability to accommodate uneven or missing data, and the ability to increase the power of small samples (Mota et al., 2023, Hamner and Tan, 2022).

Data were verified to confirm the linearity of the relationship between the dependent variable and the fixed-effects (Monsalves et al., 2020) and ensure the normality and independence of the random effects (Monsalves et al., 2020). Homoscedasticity of the residuals across all levels of the independent variables and independence of observations were verified

(Monsalves et al., 2020, Hamner and Tan, 2022). Furthermore, the residuals' generated quantile-quantile plots (Q-Q plots) closely followed the reference line, suggesting that the residuals were approximately normally distributed (Harrison et al., 2018). Verification of all assumptions yielded data suitable for analysis. In the analysis conducted using the lme4 (version 1.1.35.1) and Afex (version 1.3.0) packages in R (Statistical Computing, Vienna, Austria, Version 4.3.2), the linear mixed-effects model was specified with a combination of fixed and random effects. The effect of time was modeled as a fixed effect containing two levels (pre, post), while controlling for the effects of group and maturity status. The effect of the training group was modelled as a fixed effect with three levels (STG, PTG, CG) while holding time and maturity status constant. The fixed main effect of maturity status (LPUB, MPUB, PRE, EPUB) on the dependent variable was assessed while controlling for group and time. Fixed effects were assessed relative to a reference status. The effect of time was assessed relative to pre-test, the effect of training group relative to the control group, and the effect of maturity status about EPUB status. The random-effects were structured to account for variability at the individual level, indicated by (1|Code) in the model formula, signifying random intercepts for each level of the Code variable. Group x time interactions were investigated, which allowed the assessment of whether participants engaged in different training methods (PTG or STG) significantly differed in their change in the outcome over time relative to a control group while controlling for maturity status. Fixed effects estimates are noted by regression coefficient estimates, or beta coefficients (β).

To determine if the study was sufficiently powered, a post hoc power analysis was performed using G*Power version 3.1.9.7 (Faul et al., 2007). Given that G*Power does not support a linear mixed effect model, this analysis was approximated using the category of linear multiple regression, fixed model, R^2 , deviation from zero. The parameters were entered as follows, effect size 0.15-0.3, statistical significance, $\alpha = 0.05$, total sample size, 48, number of predictors, three (Moran et al., 2023, Faul et al., 2007). According to these parameters, the achieved power was between 0.56 and 0.87.

7.4 RESULTS

The results of the LMM, including the mean, SD, and within-group differences, and difference to the control group are presented in Tables 7.4 and 7.5 and Figures 7.1-7.2. The beta coefficients (β), standard error (SE), and associated p-value (p) for all group x time interactions are also presented in Tables 7.4-7.5.

7.4.1 Fixed effects

7.4.1.1 Fixed effect of time

Time as a fixed main effect had no significant influence on absolute and relative leg stiffness, whereas there was a statistically significant effect of time on absolute BJ ($\beta = -8.26$, $p = 0.036$) and RelBJ ($\beta = -0.12$, $p = 0.021$). These variables were significantly smaller at post-test in reference to the pre-test scores, independent of training group or maturation. There was no significant effect of time on any other horizontal jump or hop measures. Within group differences in leg stiffness are presented in Figure 7.1 and 7.2

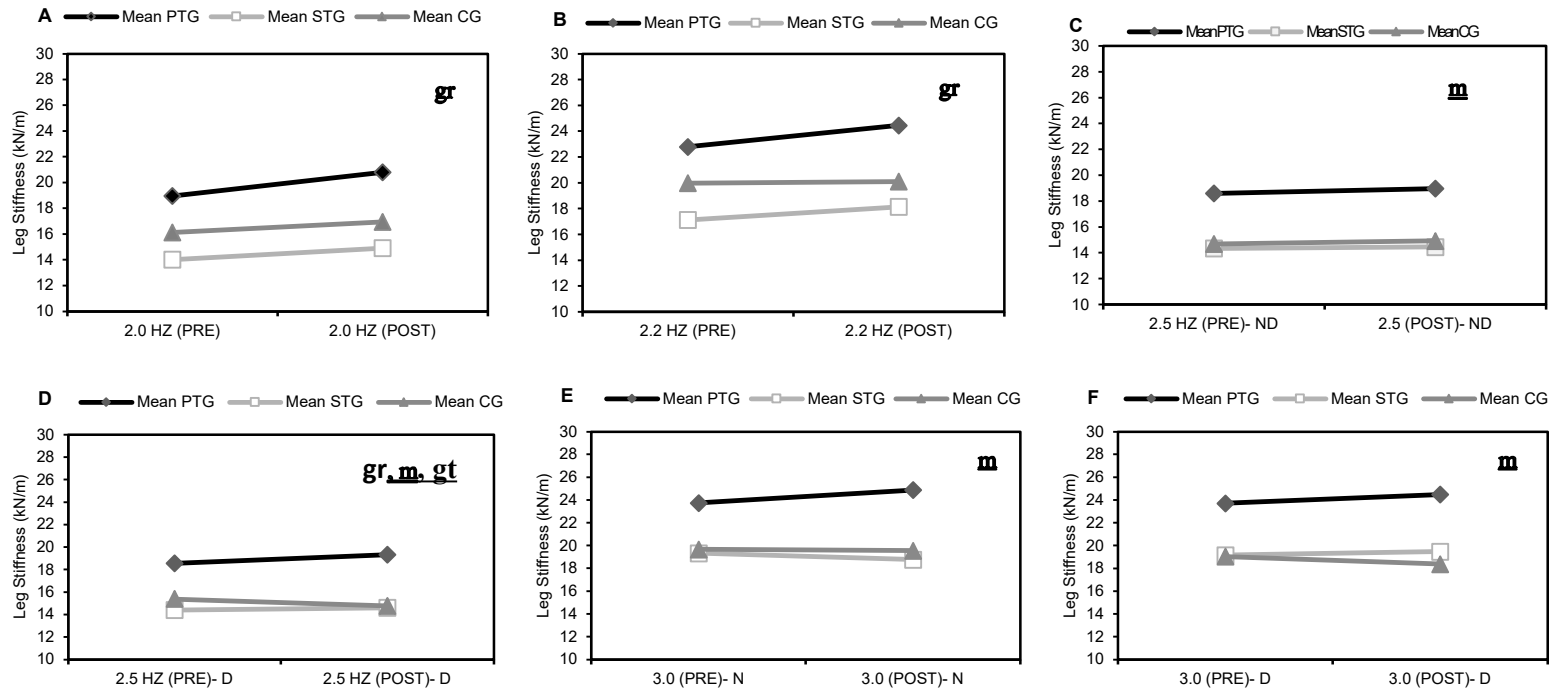


Figure 7.1. Within-group differences in absolute leg stiffness: A = 2.0 Hz; B = 2.2 Hz; C = 2.5 Hz non-dominant leg; D = 2.5 Hz dominant leg; E = 3.0 Hz non-dominant leg; F = 3.0 Hz dominant leg; t = significant effect of time; gr = significant effect of group; m = significant effect of maturation; gt = significant group by time interaction; D = dominant leg; ND = non-dominant leg; kN/m = kilonewtons per meter.

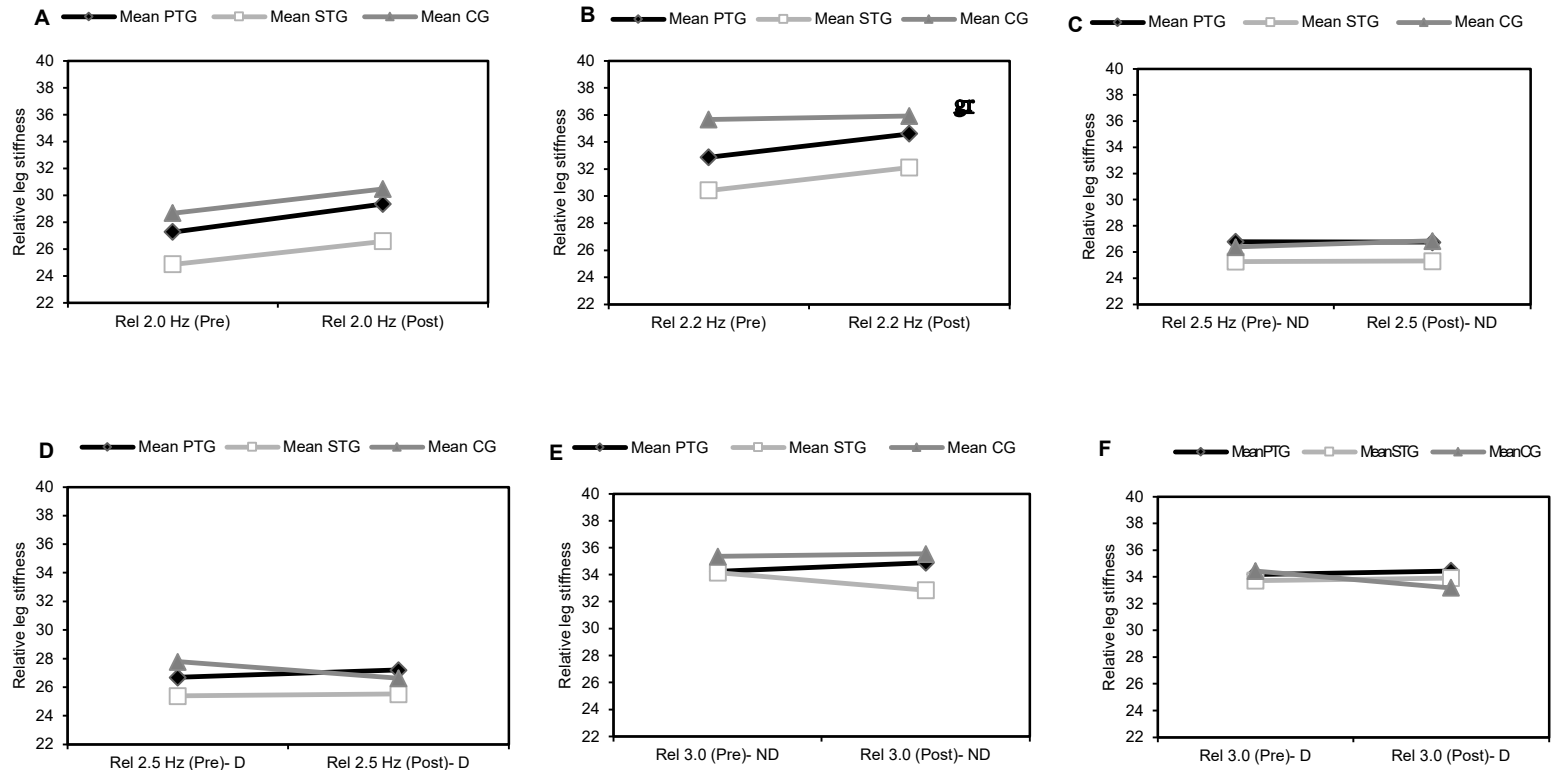


Figure 7.2. Within-group differences in relative leg stiffness (dimensionless); A = 2.0 Hz; B = 2.2 Hz; C = 2.5 Hz non-dominant leg; D = 2.5 Hz dominant leg; E = 3.0 Hz non-dominant leg; F = 3.0 Hz dominant leg; t = significant effect of time; gr = significant effect of group; m = significant effect of maturation; gt = significant group by time interaction; D = dominant leg; ND = non-dominant leg.

Table 7.4. Absolute and relative leg stiffness relative to the control group

Variable	CG Mean	CG Mean	PTG Mean	D/f to	PTG Mean	D/f to	STG Mean	D/f to	STG Mean	D/f to
	(kN/m) ± SD	(kN/m) ±	(kN/m) ± SD	CG	(kN/m)	CG %	(kN/m) ±	CG	(kN/m) ± SD	CG %
	Pre	SD	Pre	%	Kleg only	Post	SD	%	Post	Post
Kleg 2.0 Hz ^{gr}	16.12 ± 6.32	16.94 ± 5.18	18.96 ± 4.40	17.60	20.79 ± 5.32	22.70	14.01 ± 3.17	-13.10	14.91 ± 2.66	-12.00
Kleg 2.2 Hz ^{gr}	19.98 ± 7.03	20.11 ± 7.44	22.79 ± 4.91	14.10	24.45 ± 5.24	21.60	17.13 ± 4.06	-14.20	18.15 ± 3.33	-9.70
Kleg 2.5 Hz ND ^m	14.70 ± 4.75	14.93 ± 4.80	18.61 ± 2.95	26.60	18.98 ± 3.18	27.10	14.35 ± 3.40	-2.30	14.46 ± 3.02	-3.10
Kleg 2.5 Hz D ^{gr,m,gt}	15.39 ± 4.37	14.77 ± 4.83	18.55 ± 3.14	20.60	19.33 ± 3.54	30.90	14.41 ± 3.28	-6.40	14.60 ± 3.17	-1.20
Kleg 3.0 Hz ND ^m	19.67 ± 6.28	19.57 ± 5.70	23.75 ± 3.93	20.80	24.88 ± 5.49	27.20	19.33 ± 4.78	-1.70	18.78 ± 4.24	-4.00
Kleg 3.0 Hz D ^m	19.05 ± 5.81	18.39 ± 5.98	23.72 ± 4.02	24.50	24.49 ± 4.80	33.10	19.17 ± 4.94	0.70	19.48 ± 4.51	5.90
RelKleg 2.0 Hz	28.68 ± 5.59	30.47 ± 3.94	27.27 ± 5.16	-4.90	29.35 ± 6.19	-3.70	24.87 ± 3.16	-13.30	26.59 ± 4.86	-12.80
RelKleg 2.2 Hz ^{gr}	35.67 ± 4.79	35.92 ± 6.79	32.88 ± 6.10	-7.80	34.61 ± 6.30	-3.70	30.43 ± 4.56	-14.70	32.12 ± 4.61	-10.60
RelKleg 2.5 Hz ND	26.40 ± 3.73	26.86 ± 4.38	26.80 ± 3.42	1.50	26.77 ± 2.35	-0.30	25.28 ± 1.71	-4.20	25.32 ± 1.84	-5.70
RelKleg 2.5 Hz D	27.79 ± 2.71	26.64 ± 4.94	26.70 ± 3.48	-3.90	27.22 ± 2.87	2.20	25.39 ± 1.72	-8.60	25.53 ± 1.93	-4.20
RelKleg 3.0 Hz ND	35.36 ± 5.51	35.56 ± 6.50	34.26 ± 4.87	-3.10	34.90 ± 4.45	-1.80	34.16 ± 4.92	-3.40	32.86 ± 3.30	-7.60
RelKleg 3.0 Hz D	34.45 ± 6.01	33.19 ± 6.42	34.19 ± 4.99	-0.70	34.46 ± 4.75	3.80	33.73 ± 4.31	-2.10	33.92 ± 2.31	2.20

Kleg = absolute leg stiffness; Rel = relative; RelKleg = relative leg stiffness; Hz = hertz; ND = non-dominant; D = dominant; Pre = pre-test; Post = post-test; SD = standard deviation; PTG = plyometric training group; STG = sprint training group; D/f = raw difference; CG = control group; kN/m = kilonewtons per meter (absolute leg stiffness conditions only).

t = significant effect of time; gr = significant effect of group; m = significant effect of maturation; gt = significant group by time interaction.

Table 7.5. Absolute and relative jump and hop distance relative to the control group

Variable	CG Mean (cm) Abs only Pre	CG Mean (cm) ± SD Post	PTG Mean (cm) ± SD Pre	D/f to CG % Pre	PTG Mean (cm) ± SD Post	D/f to CG % Post	STG Mean (cm) ± SD Pre	D/f to CG % Pre	STG Mean (cm) ± SD Post	D/f to CG % Post
BJ ^{t,gr,gt}	148.13 ± 19.87	139.87 ± 22.65	187.97 ± 20.42	26.90	184.84 ± 18.19	32.20	156.60 ± 22.28	5.70	158.38 ± 29.15	13.20
SBHR ^{gr}	124.44 ± 23.34	122.49 ± 25.22	160.98 ± 18.40	29.40	163.85 ± 13.39	33.80	139.61 ± 23.19	12.20	143.17 ± 26.24	16.90
SBHL ^{gr}	124.53 ± 22.04	123.77 ± 25.41	166.10 ± 18.30	33.40	168.82 ± 15.61	36.40	139.18 ± 20.07	11.80	145.50 ± 22.72	17.60
TBJ ^{gr}	421.81 ± 63.48	432.86 ± 71.79	568.17 ± 56.57	34.70	564.75 ± 52.65	30.50	488.41 ± 60.77	15.80	478.11 ± 76.03	10.50
TBHR ^{gr,m}	363.10 ± 75.39	382.15 ± 95.97	484.86 ± 58.27	33.50	488.57 ± 50.10	27.80	400.26 ± 79.75	10.20	420.92 ± 73.96	10.10
TBHL ^{gr}	360.27 ± 79.08	379.46 ± 93.76	484.58 ± 56.31	34.50	494.68 ± 61.83	30.40	397.82 ± 70.81	10.40	412.77 ± 63.24	8.80
RelBJ ^t	2.08 ± 0.22	1.96 ± 0.25	2.33 ± 0.31	12.40	2.29 ± 0.28	17.00	2.08 ± 0.19	0.10	2.08 ± 0.30	6.20
RelSBHR	1.74 ± 0.26	1.70 ± 0.24	2.00 ± 0.27	14.70	2.03 ± 0.23	19.00	1.86 ± 0.26	6.60	1.88 ± 0.25	10.00
RelSBHL ^{gr}	1.74 ± 0.23	1.73 ± 0.27	2.06 ± 0.26	18.30	2.09 ± 0.23	21.00	1.85 ± 0.21	6.30	1.91 ± 0.22	10.70
RelTBJ ^{gr,gt}	5.92 ± 0.79	6.05 ± 0.76	7.05 ± 0.87	19.10	6.99 ± 0.82	15.50	6.49 ± 0.57	9.60	6.29 ± 0.83	3.90
RelTBHR	5.07 ± 0.79	5.31 ± 0.98	6.02 ± 0.89	18.80	6.05 ± 0.77	13.90	5.31 ± 0.86	4.60	5.53 ± 0.80	4.20
RelTBHL	5.03 ± 0.87	5.28 ± 1.01	6.01 ± 0.81	19.40	6.12 ± 0.86	15.90	5.27 ± 0.71	4.80	5.41 ± 0.58	2.50

BJ = broad jump; SBHR = single broad hop right; SBHL = single broad hop left; TBJ = triple broad jump; TBHR = triple broad hop right; TBHL = triple broad hop left; Rel = Relative (LL); Pre = pre-test; Post = post-test; SD = standard deviation; PTG = plyometric training group; STG = sprint training group; D/f = raw difference; CG = control group.

t = significant effect of time; gr = significant effect of group; m = significant effect of maturation; gt = significant group by time interaction.

7.4.2.2 Fixed effect of group

There was a statistically significant effect for the STG compared to the CG on absolute leg stiffness assessed by bilateral hopping at 2.0 Hz ($\beta = -3.491, p = 0.047$) and 2.2 Hz ($\beta = -4.373, p = 0.028$) and unilateral hopping on the dominant leg at 2.5 Hz ($\beta = -2.444, p = 0.039$). More specifically, the absolute leg stiffness values of the STG were significantly lower compared to the values of the CG independent of time and maturity status. Relative leg stiffness was significantly lower for the STG than the CG during bilateral hopping at 2.2 Hz ($\beta = -5.571, p = 0.025$). Regarding the horizontal tasks, the PTG had significantly higher absolute BJ ($\beta = 28.104, p = 0.005$), SBHR ($\beta = 22.759, p = 0.009$), SBHL ($\beta = 28.508, p = 0.001$), TBJ ($\beta = 107.339, p < 0.01$), TBHR ($\beta = 70.332, p = 0.012$) and TBHL ($\beta = 74.859, p = 0.008$). In contrast, only absolute TBJ revealed a significant STG effect ($\beta = 107.339, p < 0.01$). More precisely, the PTG was associated with a larger absolute jumping and hopping distances relative to the CG, regardless of time point or maturity status. For relative horizontal tasks, significant PTG effects were revealed for RelSBHL ($\beta = 0.268, p = 0.014$) and RelTBJ ($\beta = 1.025, p = 0.006$). More precisely, the PTG was associated with larger relative jumping and hopping distances than the control group, regardless of time point or maturity status. No significant STG effects were realized for any other relative horizontal variables.

7.4.2.3 Fixed effect of maturity status

The fixed effect of maturity status is displayed graphically in Figure 7.3. Absolute leg stiffness demonstrated statistically significant effects of LPUB for the non-dominant leg ($\beta = 4.171, p = 0.017$) and dominant leg ($\beta = 4.299, p = 0.017$) while hopping at 2.5 Hz, non-dominant leg ($\beta = 5.868, p = 0.017$) and dominant leg ($\beta = 6.114, p = 0.011$) while hopping at 3.0 Hz. More specifically, compared to EPUB, LPUB status was associated with significantly larger leg stiffness values during hopping at the stated frequencies. No statistically significant effects of maturity status were observed for relative leg stiffness. For absolute horizontal jumping and hopping, significant LPUB effects were demonstrated for TBHR only ($\beta = 90.376, p = 0.024$).

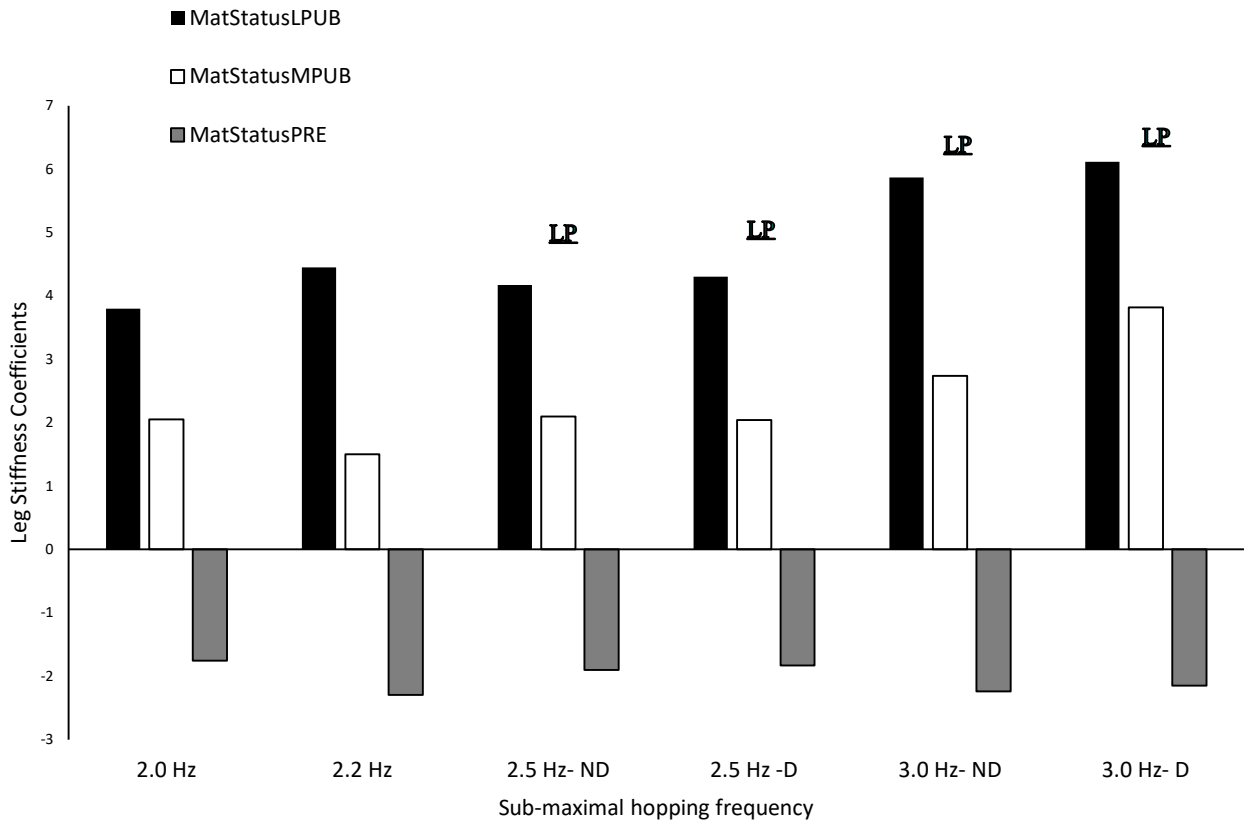


Figure 7.3. Leg stiffness coefficients per maturity status.

Note: MatStatus = maturity status; LPUB = late pubertal; MPUB = mid-pubertal; PRE = pre-pubertal; Hz = Hertz; LP = significant effect of LPUB; ND = non-dominant leg; D = dominant leg

7.4.3 Interaction effects- group x time

During dominant leg hopping at 2.5 Hz, the PTG demonstrated a significant interaction effect ($\beta = 1.392, p = 0.023$). This result could indicate an elevated improvement from pre-test to post-test in absolute leg stiffness during dominant leg sub-maximal hopping at 2.5 Hz compared to the CG. No other interaction effects were realized for any group's leg stiffness during sub-maximal hopping. BJ distance for the STG revealed a significant interaction term ($\beta = 10.044, p = 0.045$), suggesting a higher enhancement in BJ performance for the STG compared to the CG. The RelTBJ for STG demonstrated a significant interaction ($\beta = -0.334, p = 0.041$), indicating a significant decrease in RelTBJ performance in the STG compared to the CG.

Table 7.6. LMM beta coefficients, SE, p-value for group x time interactions for leg stiffness

Variable	PTG (<i>n</i> = 22)			STG (<i>n</i> = 16)		
	β	SE	<i>p</i>	β	SE	<i>p</i>
2.0 Hz	1.01	1.26	0.43	0.07	1.34	0.96
2.2 Hz	1.53	1.29	0.24	0.89	1.36	0.52
2.5 Hz N	0.14	0.56	0.80	-0.13	0.59	0.83
2.5 Hz D	1.39*	0.59	0.02	0.81	0.62	0.20
3.0 Hz N	1.23	1.12	0.28	-0.45	1.19	0.71
3.0 Hz D	1.42	0.89	0.12	0.96	0.95	0.32
Rel 2.0 Hz	0.29	2.06	0.89	-0.07	2.18	0.97
Rel 2.2 Hz	1.49	2.04	0.47	1.45	2.15	0.51
Rel 2.5 Hz ND	-0.50	0.81	0.55	-0.42	0.86	0.63
Rel 2.5 Hz D	1.66	1.00	0.10	1.28	1.06	0.23
Rel 3.0 Hz ND	0.45	1.78	0.80	-1.50	1.88	0.43
Rel 3.0 Hz D	1.53	1.55	0.33	1.45	1.64	0.38

Hz = hertz; ND = non-dominant leg; D = dominant leg; Rel = relative (BM/LL); PTG = plyometric training group; STG = sprint training group; β = beta coefficients; SE = standard error.

* = significant group by time interaction; *n* = number of participants.

Table 7.7. LMM beta coefficients, SE, p-value for group x time interactions for horizontal jumps and hops

Variable	PTG (<i>n</i> = 22)			STG (<i>n</i> = 16)		
	β	SE	<i>p</i>	β	SE	<i>p</i>
BJ	5.13	4.61	0.27	10.04*	4.87	0.05
SBHR	4.83	4.86	0.33	5.51	5.14	0.29
SBHL	3.48	3.60	0.34	7.08	3.80	0.07
TBJ	-14.48	11.21	0.20	-21.35	11.85	0.08
TBHR	-15.33	12.58	0.23	1.61	13.30	0.90
TBHL	-9.09	11.80	0.45	-4.24	12.47	0.74
RelBJ	0.07	0.06	0.23	0.12	0.06	0.07
RelSBHR	0.07	0.06	0.30	0.06	0.07	0.41
RelSBHL	0.04	0.05	0.36	0.08	0.05	0.14
RelTBJ	-0.19	0.15	0.20	-0.33*	0.16	0.04
RelTBHR	-0.21	0.16	0.20	-0.01	0.17	0.95
RelTBHL	-0.14	0.16	0.38	-0.11	0.16	0.52

Hz = hertz; N = non-dominant leg; D = dominant leg; Rel = relative (LL); PTG = plyometric training group; STG = sprint training group; β = beta coefficients; SE = standard error; *n* = number of participants.

* = significant group by time interaction.

7.5 DISCUSSION

This was the first study to explore the effects of linear sprint training and horizontal plyometric training on absolute and relative leg stiffness, horizontal jumping, and hopping distance. The main findings revealed that compared to the CG, the PTG significantly improved absolute leg stiffness from pre- to post-intervention while hopping at 2.5 Hz on the left (dominant) leg. Specifically, the PTG improved, while the CG declined in performance. Furthermore, the effect of training over time as noted by the beta coefficients, was higher for the PTG ($\beta = 1.392, p = 0.023$) than the STG ($\beta = 0.808, p = 0.202$). Significant fixed effects of maturity status were observed in LPUB for absolute leg stiffness during all unilateral hopping tests. Significant fixed effects of maturity status were observed in LPUB for absolute TBHR, whereas TBHL approached significance ($p = 0.052$). The findings of this study led to the acceptance of the primary hypothesis.

7.5.1 Effect of training on leg stiffness

The absolute leg stiffness of the dominant leg during unilateral hopping at 2.5 Hz showed a significant improvement from pre- to post-intervention in the PTG compared to the CG. Moreover, the PTG's effect over time relative to the CG exceeded that of the STG, highlighting plyometric training as a more effective stimulus for leg stiffness adaptations.. Although both PTG and STG interventions utilized horizontally oriented stimuli, (Millett et al., 2016), it is likely that the PTG exercises led to greater vertical projection of the body, characterized by longer flight times (Meyers et al., 2019, Lloyd et al., 2012a), leading to a higher VGRF upon subsequent ground contact (Millett et al., 2018). Conversely, sprinting minimizes vertical projection of the body (Struzik et al., 2021). Repeated exposures to forceful stretch-loading for the PTG may have resulted in a higher active state of the muscle before beginning the upward phase (Turner and Jeffreys, 2010), and higher propulsive impulse (Moeskops et al., 2020). Considering the substantial force and impulse necessary for projecting the body during plyometric exercises, heightened neuromuscular control mechanisms of stiffness might additionally account for the observed changes associated with plyometrics. For instance, plyometric training may have enhanced the capacity to recruit and activate motor units, augment extensor muscle activity and raise overall force production

(Oliver and Smith, 2010). This augmented force production, particularly with an amplified rate of force generation, improves the capacity to counteract the downward collapse of the body and facilitates shorter ground contact times and higher propulsive impulse (Chang and Wang, 2018, Lloyd et al., 2011c, Christoforidou et al., 2017, Moeskops et al., 2020). Additionally, repeated exposures to plyometric training in this study may have enhanced the magnitude of muscle preactivation (Christoforidou et al., 2017, Moeskops et al., 2022a). Adequate muscle preactivation can prepare the limb for ground contact by facilitating an earlier and faster rise in muscle action before and immediately upon ground contact (Lazaridis et al., 2010). The amplitude and timing of the stretch-reflex may also regulate muscle stiffness by acting as a trigger for earlier initiation of muscle action in response to a rapid stretch (Oliver and Smith, 2010, Sinkjaer et al., 1988). Together, these neurological mechanisms result in a quicker transition from the eccentric to concentric phase of the SSC, more efficient utilization of stored elastic energy, and an adequate rise of the force necessary to project the body during the propulsive phase (Waugh et al., 2017, Lloyd et al., 2012a, Radnor et al., 2017, Tumkur Anil Kumar et al., 2021, Markovic and Mikulic, 2010). Therefore, our findings indicate that plyometric training may offer a more potent stimulus for change in the neuromuscular properties that regulate stiffness (Radnor et al., 2017). It is unknown whether this intervention was of sufficient length to elicit substantial dimensional and material muscle and tendon adaptations (Radnor et al., 2017, Moran et al., 2023), but a combination of neuromuscular properties and musculotendinous dimensional/material adaptations together could explain the change (Radnor et al., 2021, Tumkur Anil Kumar et al., 2021).

Our data indicate that sprinting might not foster significant leg stiffness adaptations while hopping at 2.5 Hz when considering the effect of sprint training over time on leg stiffness. It is also possible that sprint training failed to provide a sufficient maximum speed stimulus to induce leg stiffness adaptations in young girls. While researchers have indicated that young girls can attain maximum speeds within 20 meters (Moeskops et al., 2021), it remains uncertain whether the foot contacts made during the acceleration phase of sprint repetitions provided a significant stimulus for inducing stiffness adaptations in young girls. Contact times during the acceleration phase are usually longer (Nagahara et al., 2019), less spring-like in force application (Nagahara and Zushi, 2016), with smaller vertical ground reaction

force (Colyer et al., 2020). Stiffness has also been associated with max velocity more than acceleration in youth (Chelly and Denis, 2001). The coefficients for the effect of STG over time on leg stiffness was higher at 3.0 Hz ($\beta = 0.96$, $p = 0.315$) than at 2.5 Hz on the dominant leg ($\beta = 0.81$, $p = 0.2$). It is possible that the shorter contact times produced during sub-maximal hopping at 3.0 Hz are more reflective of the contact times (~0.130 to 0.20 s) during sprinting in girls of varied maturity and age (Millett et al., 2018, Colyer et al., 2020, Nagahara et al., 2019). Data from Chapter 3 of this thesis reported sub-maximal hopping (3.0 Hz) contact times of ~ 0.192 s, while Chapter 5 and 6 demonstrated an average CT of 0.16 s during sprinting and 0.23 s during sub-maximal hopping at 2.5 Hz. Contact times may be higher during vertical jumping exercises compared to sprinting. Similarly, vertical ground reaction forces during vertical jumping exercises are higher compared to sprinting over 50 m (Colyer et al., 2020, Moeskops et al., 2022b, Millett et al., 2018). It is possible that the smaller ground reaction forces during sprint training did not stimulate stiffness adaptations as well as plyometric training. If the girls in the present study produced ground reaction forces, contact times and sprint velocities during training that reflect those of the previous literature, then these mechanisms may explain the decreased potency of sprint training for leg stiffness adaptations. It remains possible that longer sprint distances, where girls run at or near their top speed for longer may have allowed more contacts requiring stiffer ground contact strategies and thus allow sprint training to be more effective in producing stiffness adaptations.

7.5.2 Effect of maturity status on leg stiffness

In the current study, late pubertal maturity status was associated with significantly higher absolute leg stiffness on the dominant and non-dominant legs while hopping at 2.5 Hz and 3.0 Hz. No effect of maturity status was observed for absolute leg stiffness during bilateral hopping or any relative leg stiffness hopping condition. This finding may indicate a stronger effect of LPUB maturity status on absolute leg stiffness assessed unilaterally in girls compared to EPUB maturity status. This partly agrees with Laffaye et al. (2016) who found that absolute leg stiffness experienced a significant rise in girls between age 15-16 during maximal hopping, an age range reflecting later pubertal development. However, our findings contrast Lehnert et al. (2020), who reported a plateau in absolute leg stiffness for 15–16-year-

old girls during bilateral sub-maximal hopping at 2.5 Hz, coinciding with their transition from mid-PHV to post-PHV maturity status. The discrepancies between the current study, Laffaye et al. (2016) and Lehnert et al. (2020), may arise from variations in maturity indicators, the assessment of leg stiffness based on maturity status rather than age, or differences in athletic tasks—such as comparing maximal to sub-maximal efforts and bilateral to unilateral movements. For instance, studies on bilateral sub-maximal hopping have reported significantly lower absolute leg stiffness across various frequencies in children compared to adults, while contact times remain similar between the two groups. Conversely, for relative leg stiffness, children's leg stiffness is significantly higher at 2.5 Hz but significantly lower below and above 2.5 Hz (Waugh et al., 2017). Interestingly, during unilateral hopping, absolute leg stiffness was similar between children and adults, with CT significantly shorter in children across a range of frequencies, and relative leg stiffness significantly higher in children (Beerse and Wu, 2016). Unfortunately, child-adult differences or differences between consecutive ages may not reflect differences from one maturity stage to the next, given that a particular stage will reflect several years of chronological age groups collectively (Cumming et al., 2017). Therefore, more research is required where training groups are categorized according to maturity.

Training-related changes in leg stiffness at 2.5 Hz on the dominant leg exceeded the within-subject error (CV%) outlined in Chapter 3. More specifically, the training-related change on the dominant leg can be considered clinically meaningful (Turner et al., 2015). The training-related modifications of the remaining hopping conditions did not exceed the previously established within-subject error, and therefore interpretations from these protocols should be treated with caution. The significant change in leg stiffness at 2.5 Hz on the dominant leg and not the non-dominant leg, may indicate that the dominant leg drives bilateral leg stiffness improvements, although this is speculative. Unilateral leg stiffness assessment in young girls is worth further consideration for researchers, particularly comparing maturity-related developments of bilateral and unilateral hopping at the same 2.5 Hz frequency.

7.5.3 Horizontal hopping and jumping

The data (Table 7.5, 7.7) revealed that most absolute and relative broad hopping conditions in the PTG and STG experienced non-significant increases over time relative to the CG. Conversely, the absolute TBJ of the PTG and STG decreased over time, albeit non-significantly relative to the CG. In contrast, RelTBJ of the STG decreased significantly over time relative to the CG, while BJ of the STG significantly increased relative to the CG. All jump and hop conditions fell below the within-subject error (CV%) outlined in Chapter 4, suggesting that the observed increases were not clinically significant (Turner et al., 2015). These findings contradict previous literature on plyometric training in girls, which has shown that broad jump distance increased (ranging from 3-24%) in response to six to ten weeks of unilateral and bilateral multi-directional plyometric training (Kong, 2018, McCormick et al., 2016, Gaamouri et al., 2023). There is a lack of research evaluating broad hopping capabilities following plyometric training interventions. However, the current group's results align with earlier studies that assessed the triple broad hop test after combined training programs. For instance, a cluster randomized control trial in 13–18-year-old girls conducted by (Steffen et al., 2013) observed 0% and 3% changes in left and right triple hop distance, respectively, after 7-11 weeks of FIFA 11+ training. Additionally, Noyes and Barber-Westin (2015), administered a 6-week combined muscle strength, speed, muscle endurance, plyometric and agility program. They reported a significant 2% increase in triple hop distance. These findings suggest that improvements in triple broad hop distance may be more challenging to achieve compared to broad jump improvements. Alternatively, broad jump tests might be more prevalent in the literature, which could suggest a greater emphasis on this test throughout the literature and greater familiarity of this task compared to hopping tasks.

Regarding linear sprint training, other than the BJ, there were no significant improvements in jumping or hopping ability due to sprint training relative to the CG. Furthermore, despite sprint training being a horizontally oriented training stimulus, the coefficients were lower than those of the PTG, indicating a diminished effect on horizontal jumping and hopping distance. Only one study was found where researchers evaluated the effect of overground sprint training only in girls (Gevat et al., 2012). Other studies have combined sprint training

with other methods like muscular strength training, muscular endurance training, agility and plyometrics (Noyes and Barber-Westin, 2015, Mathisen and Pettersen, 2015).

Despite the intermuscular coordination and fast limb movements completed in sprinting (Rumpf et al., 2012), it is possible that the propulsive forces produced during sprinting are not sufficient to produce adaptations in horizontal jumping and hopping in young girls (Uzunov, 2009, Standing and Maulder, 2019, Colyer et al., 2020). Sprinting requires sufficient propulsive force to project the body in the air long enough to reposition the swing leg to strike again and to maintain forward momentum (Uzunov, 2009, Standing and Maulder, 2019, Colyer et al., 2020). This may not reflect the same demands as projecting the body into the air and across the ground during a jump or hop. The optimal training parameters for maximizing horizontal jump distance in young girls remain unclear. Additionally, the factors that most significantly influence training programs among girls have yet to be elucidated. It is recommended that future studies incorporate analyses aimed at determining the most effective program parameters for enhancing performance in horizontal jumping and hopping tasks.

7.6 LIMITATIONS

There are several limitations worthy of consideration in the current study. *Firstly*, the sample size and participant maturity characteristics did not allow participants to be grouped by maturity status. To account for the effects of maturity status, linear mixed-effect models were used to control for maturity status during the analysis statistically (Mota et al., 2023). *Secondly*, the lack of distinct maturity groups per training method required a robust and flexible statistical method to account for these limitations. The authors acknowledge that despite statistical controls, the lack of group assignment according to maturity status may still introduce some confounding effects that could influence the interpretation of the impact of the training interventions. A linear mixed-effects model has the benefit of being able to primarily accommodate for these limitations during the analysis of fixed and random effects on the dependent variable (Hamner and Tan, 2022). The authors acknowledge that exercise load may have been affected when acute regressions were administered to athletes while they

improved their technical proficiency. Many athletes do not perform exercises with high technical proficiency right away, so learning considerations are a reality of exercise interventions, especially for youth. However, the author desired to maintain a high level of safety and effectiveness for all participants entrusted to him. *Finally*, while skeletal age assessments are viewed as the gold standard measure of biological maturation, these were unavailable, and instead, a non-invasive estimation of maturity status was used. This method carries a lower level of error in girls than other non-invasive methods (Lloyd et al., 2014b, Parr et al., 2020).

7.7 CONCLUSION AND PRACTICAL RECOMMENDATIONS

This study examined the effects of sprint and plyometric training on leg stiffness and horizontal jumping in young girls. Horizontal plyometric training significantly improved absolute leg stiffness during unilateral hopping on the dominant leg over time compared to a control group. This finding underscores the effectiveness of plyometric training in enhancing absolute leg stiffness. Conversely, sprint training did not yield significant stiffness adaptations over time relative to the control group, indicating potential protocol limitations or limitations of sprint training as a stimulus for leg stiffness development in young girls. Maturity status influenced leg stiffness, with late pubertal girls exhibiting higher stiffness during unilateral hopping at multiple frequencies.

This research highlights the importance of tailored training approaches to optimize performance in young female athletes. Specifically, plyometric training that emphasizes large forces executed with short ground contact times promotes muscle preactivation and substantial stretch-reflex contributions, which are crucial for effective ground force application and optimal stiffness levels (Moran et al., 2023, Lloyd et al., 2012c). Coaches can integrate plyometric exercises into athletes' training regimens to enhance leg stiffness, for sports actions requiring explosive movements. Therefore, coaches may consider integrating age-appropriate plyometric exercises to enhance physical development and performance capabilities in young athletes. Introducing plyometric training at an early stage can lay a solid foundation for future athletic development. As these athletes grow and their

training intensifies, the neuromuscular adaptations from early plyometric training can contribute to superior performance and reduced injury risk (Moran et al., 2018a).

CHAPTER 8. THE EFFECT OF PLYOMETRIC TRAINING AND MODERATING VARIABLES ON STRETCH- SHORTENING CYCLE FUNCTION AND PHYSICAL QUALITIES IN FEMALE POST PEAK HEIGHT VELOCITY VOLLEYBALL PLAYERS

8.0 PRELUDE

Chapter 7 examined the effects of sprint and plyometric training on leg stiffness and horizontal jumping in young girls relative to a control group while controlling for maturity status. Horizontal plyometric training significantly improved absolute leg stiffness during unilateral hopping on the dominant leg at 2.5 Hz. However, sprint training did not yield significant leg stiffness adaptations over time, indicating potential protocol limitations or sprint training limitations as a stimulus for stiffness development in young girls. Maturity status influenced leg stiffness during all unilateral hopping conditions, with late pubertal girls exhibiting higher leg stiffness during unilateral hopping at multiple frequencies. This may also suggest that more mature girls may benefit from targeted training programs to enhance their existing leg stiffness levels. Therefore, Chapter 8 aims to explore the impact of plyometric training on leg stiffness in post-PHV girls. These findings may highlight the importance of tailored training approaches to optimize performance in youth female athletes.

This chapter comprises the following published paper:

Sylvester R, Lehnert M, Hanzlíková I and Krejčí J (2024), The effect of plyometric training and moderating variables on stretch-shortening cycle function and physical qualities in female post peak height velocity volleyball players. *Frontiers in Physiology*. 15:1346624. doi: 10.3389/fphys.2024.1346624

8.1 INTRODUCTION

The stretch-shortening cycle (SSC) involves the coupling of a stretch action and rapid shortening action, divided by a very brief pause (Pedley et al., 2020). The stretch action primarily involves an eccentric muscle action and lengthening of the tendon in series, whereas the shortening action primarily involves a concentric muscle action and a shortening of the tendon in series (Turner and Jeffreys, 2010). The SSC plays an important role in jumping ability (Idrizovic et al., 2018, Kums et al., 2005), which is a fundamental component for offensive and defensive actions in volleyball (Giustino et al., 2022). These actions require a high level of explosive ability to successfully execute these jumps within the context of a match (Lehnert et al., 2017). Jumping high and jumping quickly are relevant skills to develop in volleyball players (Rojano-Ortega et al., 2021, Fatthi and Sadeghi, 2014), both during which effective SSC function encourages more efficient eccentric and concentric phases (Idrizovic et al., 2018, Carrasco-López et al., 2019). Plyometric training can be used to improve force and power output by improving SSC function (Kums et al., 2005, Carrasco-López et al., 2019). Effective SSC function optimizes elastic energy storage and return, increases stretch-reflex contribution, and increases neuromuscular recruitment and activation (Turner and Jeffreys, 2010, Radnor et al., 2017). These potentiating mechanisms thus lead to improved control and coordination of the ground contact phase, reduced metabolic cost of movement, enhanced propulsive force, and greater force at a given velocity during the propulsive phase (Turner and Jeffreys, 2010, Flanagan and Comyns, 2008).

SSC function is governed by the effective interaction between neural, muscular and muscle-tendon structural factors (Radnor et al., 2017). The development of neural factors consists of improved recruitment and activation in the agonist muscles, improved stretch-reflex function, and improved intermuscular coordination (Asadi et al., 2017a, Grosset et al., 2005, Grosset et al., 2008, Lambertz et al., 2003, Markovic and Mikulic, 2010), while muscular factors include increased muscle size (Radnor et al., 2017). Additionally, muscle-tendon factors include increased tendon size, and improved Young's modulus, which is an indication of intrinsic material properties reflected by the stress-strain relationship (Waugh et al., 2012). Improvement in these factors may contribute to improved force production, increased rate of

force production, improved stiffness, and overall SSC function, leading to improved jump and sprint performance (Radnor et al., 2017, Tumkur Anil Kumar et al., 2021).

The neuromuscular regulatory factors that govern the SSC, develop as an individual grows and matures (Radnor et al., 2021, Radnor et al., 2017). Briefly, growth and maturation consist of the increase in size and progress towards a mature state of the body (Lloyd et al., 2014b). These changes lead to a non-linear natural development of the SSC throughout childhood and adolescence (Radnor et al., 2017). To make improvements over and above the natural development of physical qualities, a developmentally appropriate training stimulus is required (Lloyd et al., 2016a). More specifically, a training stimulus like plyometric training, targets the SSC and matches the natural adaptive processes, thus resulting in a synergistic relationship that leads to more effective adaptation (Lloyd et al., 2015a, Moran et al., 2018a). In youth, plyometric training enhances the ability to use the SSC, improving jump height, jump distance, reactive strength index (RSI) (Turner and Jeffreys, 2010, Moran et al., 2018a, Behm et al., 2017, Johnson et al., 2011), global stiffness measures (Hammami et al., 2016, Lloyd et al., 2012a), and power (Asadi et al., 2017a, Johnson et al., 2011, Lloyd et al., 2012a).

The effectiveness of a plyometric training program is dependent on the training content and the external and internal moderator variables. External moderator variables include program variables like intensity, volume, program duration, total training sessions, training frequency, (Asadi et al., 2017a, Moran et al., 2018a, Johnson et al., 2011). For outcomes like countermovement jumping, longer duration interventions with higher frequency have led to a greater adaptive response (Moran et al., 2018a), whereas for outcomes like global stiffness, shorter durations of training have proven effective in boys, but are largely unknown in girls (Ramirez-Campillo et al., 2023a, Lloyd et al., 2012a). These findings suggest that plyometric training effectiveness may differ between girls and boys due to maturational related adaptations (Ramirez-Campillo et al., 2023a, Lloyd et al., 2015a, Moran et al., 2018a). The findings also suggest that other internal moderator variables such as age, maturity, body size and generalized joint hypermobility (GJH) are also important to consider (Radnor et al., 2017, Simmonds, 2022). However, there are fewer studies in girls where researchers have evaluated the effect of plyometric training only on leg stiffness, broad jumps, broad hops

(Myer et al., 2005), triple broad hops (Noyes and Barber-Westin, 2015), or RSI compared to boys (Ramirez-Campillo et al., 2023b, Moran et al., 2018a, Bogdanis et al., 2019). *Secondly*, there are fewer studies in girls where researchers have evaluated the influence of external moderators like training volume, or internal moderators like chronological age, maturity timing or status, body size, body composition, and total GJH score (Ramirez-Campillo et al., 2023a, Moran et al., 2018a). There is a limited understanding of plyometric training effectiveness in girls during both childhood and adolescence (Ramirez-Campillo et al., 2023a, Moran et al., 2018a, Pichardo et al., 2018, Ford et al., 2011) and a limited understanding on how well the training stimulus elicits an appropriate adaptation while assessing the influence of external and internal moderating variables (Ramirez-Campillo et al., 2023a, Moran et al., 2018a). Therefore, the aims of this study are to explore the effect of horizontal plyometric training on SSC jumping and hopping and to assess the influence of training, age, body size and tissue related moderators on plyometric training in post-PHV girls. The first hypothesis of the study was that an eight-week plyometric training program with horizontal exercises would improve variables associated with stretch-shortening cycle function. The second hypothesis was that changes in variables associated with the stretch-shortening cycle would be moderated by anthropometric, functional, and training related variables such as body mass, total generalized joint hypermobility, and training volume, respectively.

8.2 METHODS

8.2.1 Participants

A total of 23 post-PHV female volleyball players between the ages of 11.8 and 15.8 years were selected to participate in this study. Local volleyball clubs in Olomouc, Czechia, were approached to ascertain their interest in participating in the research study, of which the volleyball academy VAM Olomouc agreed to participate. Afterwards the coaches approached the parents and their children to gauge their interest in participating. Ultimately most of the children and parents of VAM Olomouc agreed to participate. Inclusion criteria for initial participation included: a) participation in the highest national youth level competition in the competitive age categories U13–U16; b) being free from major orthopedic injuries (e.g.,

sprains, fractures, and tears) for at least three months prior to the start of the study; c) being free from any pain which would limit safe participation. Only participants who completed both the pre-test and post-test component of a given assessment were taken forward for analysis. These participants were also required to attend at least 75% of all training sessions (Lloyd et al., 2012a). These criteria for analysis resulted in 28 participants being excluded. All participants and parents/guardians were informed of the benefits and risks of being a part of this study. Written parental consent and written participant assent were obtained prior to commencing all data collection procedures. All data collection procedures were reviewed and approved by the Auckland University of Technology Ethics Committee (reference number 19/434) and the Ethics Committee of the Faculty of Physical Culture, Palacký University Olomouc (reference number: 15/2023). This study was conducted according to the declaration of Helsinki regarding the use of human participants.

8.2.2 Study procedures

The current study, which used a quasi-experimental design, consisted of pre-testing and post-testing, separated by an eight-week intervention, with two sessions per week. Participants attended a testing familiarization session one-week prior to the pre-testing sessions. Pre-testing consisted of two consecutive testing days. Day one consisted of a GJH test, a vertical bilateral sub-maximal hopping test, and a drop jump test, whereas day two consisted of a series of single and triple horizontal jump and hop tests and vertical unilateral sub-maximal hopping tests. Pre-testing was conducted one-week prior to the start of the intervention. For the post-testing, all tests were completed on one day, three days after the end of the intervention. During both the pre and post testing, anthropometric measurements were taken. Participants were asked to refrain from any vigorous activity for 24 hours prior to the testing sessions to limit the effects of fatigue (Turner et al., 2015). Each testing session began with a standardized warm-up which progressed from low intensity to high intensity, simple to complex and general to specific. The warm-up started with fundamental movement skills such as skipping, jogging, shuffling and dynamic stretching that targeted the calves, quadriceps, hamstrings, and adductors. Following the fundamental movement skills and dynamic stretching, vertical bilateral and unilateral sub-maximal hopping, a series of single and triple horizontal jumps and hops of progressive intensity and three sprints of progressive

intensity (60%, 90%, and 100% of maximal effort) were performed. Consistent verbal encouragement was used during all trials and sessions for each participant. All tests were performed inside the university sport facility. Tests were performed in the afternoon at the same time of the day by researchers qualified to deliver the testing and instruction.

8.2.3 Testing protocols

8.2.3.1 Anthropometric and maturity measures

Standing height, seated height, body mass, body fat percentage, and hip width (bitrochanteric and biiliac) were measured. Stature measurements were completed using a portable stadiometer (Seca 213, Seca, Hamburg, Germany), after which leg length was determined by subtracting seated height from standing height. Bioelectric impedance analysis using the Tanita SC-240 (Tanita Corporation, Tokyo, Japan) was used for body mass and body fat percentage. Lastly, hip width at the level of the iliac crest and the level of the greater trochanter were measured using large bone calipers (Model 01293, Lafayette Instrument, Lafayette, IN, USA). Biological maturity was determined with a non-invasive method based on anthropometric variables, calendar age, date of birth, and testing date. This data was used in a regression equation to estimate maturity offset and mean age at PHV (Mirwald et al., 2002). All maturity calculations were completed using the spreadsheets by Towlson et al. (2020).

8.2.3.2 Sub-maximal hopping

Sub-maximal hopping data was collected instantaneously through a mobile contact mat with attached electronic hub (SmartJump. Fusion Sport, Brisbane, Australia). The calculation of leg stiffness using the method described by Dalleau et al. (2004) is valid and reliable in youth hopping on a contact mat (Lloyd et al., 2009). Absolute leg stiffness was determined by vertical bilateral hopping at a frequency of 2.0 Hz and 2.2 Hz. Conversely, leg stiffness was determined by vertical unilateral sub-maximal hopping at two different frequencies 2.5 Hz on the right leg, 2.5 Hz on the left leg, 3.0 Hz on the right leg, and 3.0 Hz on the left leg (Lloyd et al., 2009, Beerse and Wu, 2016). Hopping at 2.5 Hz has been referred to as the hopping frequency during which stiffness is best expressed (Beerse and Wu, 2016). Each

participant completed one trial of 20 consecutive hops in which they attempted to match a frequency set by a digital metronome (Lloyd et al., 2009, Lloyd et al., 2011b, Eiling et al., 2007). To minimize fatigue, three-minutes of passive rest were given between each hop type. Participants were instructed to keep their hands on hips, jump and land on the same spot, land with legs extended and maintain their gaze forwards to minimize the additive effect of the arms and trunk (Lloyd et al., 2009). The average stiffness of all contacts was used for analysis. Contacts in which the participant jumped off the mat then back or where participants misheard instructions and stopped for too long or lost rhythm (i.e., contacts exceeded 300 ms) were excluded.

8.2.3.3 Horizontal jump and hop tests

A series of single and triple horizontal jump and hop tests were measured to the nearest 0.2 cm using a standard fiberglass tape measure. Hopping tests are typically executed by taking off and landing on the same leg, whereas jumping tests are typically executed by taking off and landing on two legs (McGann et al., 2020). The hopping tests of the present study used a protocol where participants performed a one leg take-off but a final landing on two feet.

Overall, maximum jump distance was measured over two trials each with a one-minute rest between attempts and two-minute rest between jump or hop type. The average of the two trials was used for analysis (Myers et al., 2014). Jumps were considered a fault if the participant moved their foot upon landing, or if the participant put their hands on the ground to stabilize themselves upon the final landing. For hops, the same criteria were applied, with an additional fault being recorded if the free leg touched the ground before the final landing. All jumps and hops were completed with the final landing on two feet.

8.2.3.3.1 Broad jumps

For the single and triple broad jump tests, participants started in a standing position with the toes of both feet behind the start line. Both the single and triple broad jump required the participant to start with a countermovement and jump horizontally as far as possible either

once or three consecutive times without pause respectively (Hudgins et al., 2013, Standing and Maulder, 2019, Ramirez-Campillo et al., 2015a).

8.2.3.3.2 Broad hops

For the single and triple broad hop tests, participants started in a standing position with the toes of one foot behind the start line. During the single broad hop test, participants performed a maximal hop for distance. The triple broad hop test required participants to perform three maximal consecutive hops for distance without pausing between hops and landing from the last hop on two feet (Turner and Jeffreys, 2010, Hammami et al., 2016).

8.2.3.4 Drop jump

Drop jump testing using a height of 30 cm was used to measure RSI with an Opto-jump Next system (Microgate, Bolzano, Italy) with 0.001 s accuracy. The rest interval between attempts was 30 s. Participants were instructed to place their hands on their hips, maintain their gaze forwards and step off the box towards the ground and rebound upwards. They were instructed to complete this action while getting off the ground as quickly as possible and jump as high as possible (Dalleau et al., 2004). Participants were also instructed to keep their legs extended during the flight phase of the jump and refrain from tucking their legs upwards or outwards. Trials in which the participants noticeably stepped down or noticeably jumped up from the box were not included and were asked to be repeated. Three trials were performed and the average of the two best results were used for further analysis (Sole et al., 2007). RSI was calculated as the ratio between jump height and contact time (Flanagan and Comyns, 2008, Lloyd et al., 2009). This method has been shown to be valid and reliable in youth athletes (Lloyd et al., 2009).

8.2.3.5 Generalized joint hypermobility

The GJH was tested using the Beighton score which is a valid and reliable criterion used in diagnosing this condition (Remvig et al., 2007). The score consists of five components: passive dorsiflexion and hyperextension of the fifth metacarpal joints, passive apposition of the thumbs to the forearms, passive hyperextension of the elbows and knees, and active

forward trunk flexion with knees fully extended. Note that the first four elements can be given a maximum score of two points because these are performed bilaterally (i.e., one point for each hypermobile joint), whereas the last element has a maximum score of one point. Thus, the total score ranges from zero to nine points, a higher score indicating the greater extent of joint hypermobility. The assessment was performed by an experienced physiotherapist and followed standard protocols employing a hand-held goniometer (Smits-Engelsman et al., 2011).

8.2.4 Training program

The training program consisted of various horizontally oriented plyometric exercises. These exercises were reactive in nature and involved an SSC action, meaning they required the participants to rebound off the ground and project their bodies in the horizontal direction (Lloyd et al., 2011b). The intervention ran twice a week for a period of eight weeks. Each session commenced with a warm-up consisting of five to seven minutes of problem-based movement activities, progressing from low to high intensity. The duration of each session was 35–45 minutes and session volume was tracked by distance (Ramirez-Campillo et al., 2023b). Intensity was determined based on the magnitude of eccentric loading of each exercise (Lloyd et al., 2011c, Meylan et al., 2012). Each exercise had three to six sets which required the participant to traverse 10–25 meters. Rest between sets was one to two minutes. Exercises were progressed over the course of the eight-week intervention by exercise technique complexity (Talukdar et al., 2022), intensity, and volume (Ramirez-Campillo et al., 2023a). The training intervention was implemented by an experienced strength and conditioning coach certified by the National Strength and Conditioning Association. Exercise quality was carefully observed to ensure proper execution and limit the risk of injury. Researchers routinely confirmed with the participants whether an exercise produced any pain. There were no injuries that occurred because of the intervention. Specific intervention details are in Table 8.1.

Table 8.1. Training program details.

Category	Sets	Dist. (m)	Intensity (Eccentric load)	Technique progressions	Reference
MDJLC	3–4	10–20	2 – Low	Bilateral jump, jump stick, Unilateral hop, hop stick	(Hewett et al., 1996)
MDAH	3–4	10–20	3 – Moderate	Travelling forwards, backwards, and laterally (Emphasize ankle dorsi-flexion)	(Kong, 2018, Lephart et al., 2005)
Power skipping	3–4	10–20	3 – Moderate	Skipping with rhythm - Skipping for height - Skipping for distance	(Faigenbaum et al., 2009, Konukman et al., 2008)
Gallop	3–4	10–20	3 – Moderate	Gallop with rhythm- Gallop for height- Gallop for distance	
Broad jumping	4–6	10–15	2 – Low	Broad jump with reset - Two “pump” broad jump with reset - Repeat broad jump	(McCormick et al., 2016, Cochrane and Booker, 2014, Delextrat et al., 2015)
Horizontal hopping	5– 6/leg	10–20	4/5 – Mod/High	Rhythm hops (100 Bpm) - Hop over cones - Hop for distance	(Witzke and Snow, 2000, Lephart et al., 2005)
Bounding	4–6	15–20	5 – Mod/High	Diagonal bounding - Straight bounding (short) - Straight bounding (long)	(Witzke and Snow, 2000, Kong, 2018, Hewett et al., 1996)

MDJLC: multi-directional jump landing combination; MDAH: multi-directional ankle hops; Mod: moderate; Bpm = beats per minute; Dist = distance in meters.

8.3 STATISTICAL ANALYSES

Statistical analyses were performed in MATLAB R2020a with Statistics Toolbox (MathWorks, Natick, MA, USA). Data were presented using the arithmetic mean and standard deviation. Total GJH score was also presented using the median and interquartile range. For all statistical tests, $p < 0.05$ was considered statistically significant. The normality of the data was evaluated using a Shapiro-Wilk test. Data were also plotted on a quantile-quantile plot and visually examined by a statistician. Change in the dependent variable during the training program was calculated as post-test minus pre-test ($\Delta = \text{post} - \text{pre}$). A specialized spreadsheet (Hopkins, 2015) was used to obtain changes expressed as percentages. The statistical significance of the change was evaluated using a one-sample two-tailed t-test. In addition to statistical significance, effect size was also calculated. Cohen's d was calculated as $d = M_{\Delta} / SD_{\text{pre}}$, where M_{Δ} was the mean value of delta scores and SD_{pre} was calculated from the pre-test values (baseline). The following thresholds were used to interpret the magnitude of d : trivial 0.00–0.19, small 0.20–0.49, moderate 0.50–0.79, and large ≥ 0.80 (Cohen, 1988).

Multiple regression analysis was used to determine whether individual changes in the dependent variable could be moderated by calendar age, maturity offset, body height, body mass, total GJH score, and training volume. Only linear moderators without interactions were considered. In Wilkinson notation, the regression model can be written as follows: $\Delta y \sim 1 + \text{calendar age} + \text{maturity offset} + \text{body height} + \text{body mass} + \text{total GJH score} + \text{training volume}$, where Δy is the change during the training program in the selected dependent variable. Effect size for each moderator was calculated using the eta squared statistic $\eta^2 = SS_{\text{effect}} / SS_{\text{total}}$, where SS_{effect} is the sum of squares associated with the moderator and SS_{total} is the total sum of squares (Fritz et al., 2012). The following thresholds were used to interpret η^2 : trivial 0.000–0.009, small 0.010–0.059, moderate 0.060–0.139, and large ≥ 0.140 (Cohen, 1988). To evaluate the relationship between changes in the dependent variable and one selected moderator, Pearson's correlation coefficient (r) was calculated. The following thresholds were used to interpret the magnitude of r : trivial 0.00–0.09, small 0.10–0.29, medium 0.30–0.49, and large ≥ 0.50 (Cohen, 1988).

Power analysis was performed using G*Power version 3.1.9.7 (Faul et al., 2007). The level for statistical significance was set at $\alpha = 0.05$ and the power was set at $1 - \beta = 0.80$. Under the first hypothesis, a large effect size ($d = 0.8$) was considered for the paired two-tailed t-test. The required sample size resulted in 15 participants. Under the second hypothesis, a large correlation ($r = 0.5$) was considered for the Pearson's correlation coefficient. The required sample size resulted in 26 participants. Thus, 26 participants were required to test both hypotheses.

8.4 RESULTS

8.4.1 Data normality

The characteristics of the participants are shown in Table 8.2. The median total GJH score was 3 and the interquartile range 3. Although the total GJH score was an ordinal scale ranging from 0 to 8, the Shapiro-Wilk test did not reject normality ($p = 0.20$, Table 8.2). Therefore, total GJH score was considered quasi-normal and used as a moderator in the regression analysis without any transformation. Normality was rejected for standing height ($p = 0.013$, Table 8.2). Upon examination of the quantile-quantile plot, it was found that the non-normality was due to one player whose standing height was 187.4 cm. This value was not considered as an outlier, and this player was retained in further statistical analysis. The remaining variables used as moderators in the regression analysis had normal distributions (all $p \geq 0.15$, Table 8.2).

Table 8.2. Characteristics of the participants ($n = 23$).

Variable	Mean \pm SD	<i>p</i>
Chronological age (years)	13.80 \pm 1.20	0.40
Maturity offset (years)	1.70 \pm 0.80	0.15
Mirwald APHV (years)	12.10 \pm 0.60	0.27
Standing height (cm)	165.40 \pm 6.80	0.01
Seated height (cm)	84.50 \pm 3.30	0.22
Leg length (cm)	81.00 \pm 4.80	0.36
Body mass (kg)	58.10 \pm 9.60	0.20
Body fat (%)	24.30 \pm 5.80	0.56
Total GJH score	3.50 \pm 2.10	0.20
Attended sessions	13.80 \pm 1.20	0.01
Training volume (km)	6.20 \pm 1.00	0.16

SD = standard deviation; p = statistical significance of Shapiro-Wilk normality test; APHV = age at peak height velocity; GJH = generalized joint hypermobility; n = number of participants.

The results of testing the normality of the differences between pre-values and post-values are provided in Table 8.3. The quantile-quantile plot was visually inspected for 3 out of the total 18 variables for which normality was rejected according to the Shapiro-Wilk test ($p < 0.05$). Upon examination, the deviation from normality was assessed as acceptable and parametric statistical methods were used as they are considered robust for such deviations from normality (Ghasemi and Zahediasl, 2012).

8.4.2 Training effect

The effect of the plyometric training program on the examined dependent variables is shown in Table 8.3. After plyometric training, there was a statistically significant increase in standing height (pre: 165.4 ± 6.8 , post: 165.9 ± 7.0 cm, $p = 0.001$, $d = 0.07$, trivial effect) and body mass (pre: 58.1 ± 9.6 , post: 59.0 ± 10.1 kg, $p = 0.001$, $d = 0.10$, trivial effect), which was the expected growth effect. Importantly, the effect of training on body fat (pre: 24.3 ± 5.8 , post: $24.2 \pm 5.9\%$, $p = 0.68$, $d = -0.02$, trivial effect) was not significant. Among the vertical sub-maximal hopping variables, significant increases were found for vertical bilateral hopping at 2.0 Hz (pre: 19.4 ± 4.0 , post: 21.4 ± 4.9 kN/m, $p = 0.021$, $d = 0.50$, medium effect), vertical bilateral hopping at 2.2 Hz (pre: 23.2 ± 4.4 , post: 24.9 ± 4.8 kN/m, $p = 0.049$, $d = 0.37$, small effect), and vertical unilateral hopping at 2.5 Hz left (pre: 18.9 ± 2.7 , post: 19.7 ± 3.0 kN/m, $p = 0.032$, $d = 0.32$, small effect). Examination of the broad jump variable revealed a significant decrease in broad jump distance (pre: 192 ± 21 , post: 187 ± 18 cm, $p = 0.012$, $d = -0.23$, small effect).

Table 8.3. The effect of the plyometric training program on the dependent variables

Variable	Pre-test	Post-test	Δ = post-pre	p_{sw}	p_{tt}	d
	Mean \pm SD	Mean \pm SD	Absolute (%)			
Standing height (cm)	165.4 \pm 6.80	165.9 \pm 7.00	0.5 (0.3%)	0.34	0.00	0.07
Seated height (cm)	84.5 \pm 3.30	84.7 \pm 3.30	0.2 (0.3%)	0.96	0.31	0.07
Leg length (cm)	81.0 \pm 4.80	81.2 \pm 5.00	0.2 (0.3%)	0.34	0.31	0.05
Body mass (kg)	58.1 \pm 9.60	59.0 \pm 10.10	1.00 (1.6%)	0.13	0.00	0.10
Body fat (%)	24.3 \pm 5.80	24.2 \pm 5.90	-0.10 (-0.4%)	0.40	0.68	-0.02
Sub-max hop 2.0 Hz (kN/m)	19.4 \pm 4.00	21.4 \pm 4.90	2.00 (9.5%)	0.67	0.02	0.50
Sub-max hop 2.2 Hz (kN/m)	23.2 \pm 4.40	24.9 \pm 4.80	1.60 (6.8%)	0.85	0.05	0.37
Sub-max hop 2.5 Hz right (kN/m)	19.0 \pm 2.40	19.5 \pm 2.70	0.50 (2.3%)	0.03	0.28	0.19
Sub-max hop 2.5 Hz left (kN/m)	18.9 \pm 2.70	19.7 \pm 3.00	0.90 (4.4%)	0.05	0.03	0.32
Sub-max hop 3.0 Hz right (kN/m)	23.7 \pm 4.00	25.4 \pm 4.70	1.60 (6.8%)	0.35	0.06	0.40
Sub-max hop 3.0 Hz left (kN/m)	24.1 \pm 3.40	24.9 \pm 4.00	0.80 (3.0%)	0.51	0.11	0.23
Broad jump (cm)	192 \pm 21	187 \pm 18	-5 (-2.4%)	0.84	0.01	-0.23
Broad hop right (cm)	164 \pm 16	166 \pm 13	2 (1.6%)	0.80	0.28	0.15
Broad hop left (cm)	168 \pm 17	170 \pm 14	3 (1.7%)	0.024	0.22	0.15
Triple broad jump (cm)	579 \pm 58	569 \pm 53	-10 (-1.6%)	0.34	0.13	-0.17
Triple broad hop right (cm)	493 \pm 59	496 \pm 50	3 (0.7%)	0.90	0.75	0.04
Triple broad hop left (cm)	491 \pm 55	501 \pm 60	10 (2.0%)	>0.99	0.18	0.18
Reactive strength index (m/s)	1.03 \pm 0.31	1.04 \pm 0.27	0.01 (2.0%)	0.84	0.66	0.04

SD = standard deviation; p_{sw} = statistical significance of Shapiro-Wilk normality test; p_{tt} = statistical significance of paired t-test; d = Cohen's effect size; Sub-max = sub-maximal; Hz = Hertz.

8.4.3 Effect of moderators

The results of the regression analysis are presented in Tables 8.4–8.6. Table 8.4 contains the values of each regression coefficient, Table 8.5 contains the statistical significance for each regression coefficient, and Table 8.6 contains the eta-squared for each regression coefficient. Body mass moderated the following three dependent variables: vertical unilateral hopping at 2.5 Hz right ($p = 0.010$, $\eta^2 = 0.31$, large effect), vertical unilateral hopping at 3.0 Hz right ($p = 0.035$, $\eta^2 = 0.17$, large effect), and vertical unilateral hopping at 3.0 Hz left ($p = 0.043$, $\eta^2 = 0.20$, large effect). Additionally, total GJH score moderated both the triple broad hop right ($p = 0.012$, $\eta^2 = 0.21$, large effect) and the triple broad hop left ($p = 0.034$, $\eta^2 = 0.23$, large effect). Training volume significantly moderated only triple broad hop right ($p = 0.024$, $\eta^2 = 0.16$, large effect). Calendar age (all $p \geq 0.11$), maturity offset (all $p \geq 0.12$), and body height (all $p \geq 0.077$) did not significantly moderate any dependent variable.

Interestingly, two simultaneous significant moderators were found for triple broad hop on the right leg, whereas the other dependent variables had at most one significant moderator. Therefore, a correlation analysis was performed to assess the association between changes in the dependent variable before and after the training program and one variable with pre-test values. Body mass alone was significantly correlated with the same three variables for which the regression analysis yielded a significant result mentioned above: vertical unilateral hopping at 2.5 Hz right ($r = 0.56$, $p = 0.006$, large effect, Figure 8.1A), vertical unilateral hopping at 3.0 Hz right ($r = 0.60$, $p = 0.002$, large effect, Figure 8.1B), and vertical unilateral hopping at 3.0 Hz left ($r = 0.56$, $p = 0.006$, large effect, Figure 8.1C). Total GJH score was significantly correlated only with triple broad hop left ($r = -0.43$, $p = 0.042$, medium effect, Figure 8.1E). Triple broad hop right was not significantly correlated with either total GJH score ($r = -0.33$, $p = 0.13$, Figure 8.1D) or training volume ($r = 0.39$, $p = 0.063$, Figure 8.1F). Thus, total GJH score, and training volume together significantly influenced triple broad hop right, as shown in the regression analysis, but when these moderators were taken separately, no significant correlation was found.

Table 8.4. Values of regression coefficients

Variable	Calendar age	Maturity offset	Body height	Body mass	Total GJH score	Training volume
	([y]/year)	([y]/year)	([y]/cm)	([y]/kg)	([y]/point)	([y]/km)
Body mass (kg)	1.61	-3.15	0.18	0.05	0.22	-0.22
Body fat (%)	2.22	-4.34	0.20	0.05	0.20	0.38
Sub-max hop 2.0 Hz (kN/m)	-1.93	3.63	-0.33	0.06	-0.26	-1.72
Sub-max hop 2.2 Hz (kN/m)	1.14	-3.13	-0.06	0.18	-0.09	-1.34
Sub-max hop 2.5 Hz right (kN/m)	1.22	-2.66	0.06	0.17	-0.03	0.07
Sub-max hop 2.5 Hz left (kN/m)	-0.64	0.71	-0.11	0.12	-0.09	-0.01
Sub-max hop 3.0 Hz right (kN/m)	5.88	-10.15	0.65	0.25	0.21	-0.05
Sub-max hop 3.0 Hz left (kN/m)	0.14	-0.11	-0.05	0.16	-0.08	-0.03
Broad jump (cm)	-1.84	3.97	0.03	-0.06	-1.17	3.25
Broad hop right (cm)	-9.50	17.88	-0.60	-0.30	-2.34	3.67
Broad hop left (cm)	1.32	-5.08	0.87	-0.31	-1.97	3.07
Triple broad jump (cm)	-13.98	21.43	-1.15	0.25	-4.89	4.58
Triple broad hop right (cm)	-34.42	44.26	0.21	-0.46	-8.95	17.38
Triple broad hop left (cm)	-15.68	24.08	0.21	-0.49	-8.53	11.10
Reactive strength index (m/s)	-0.15	0.24	-0.01	-0.00	-0.02	0.01

GJH = generalized joint hypermobility; [y] = unit of the dependent variable; Sub-max = sub-maximal; Hz = Hertz; kN/m = kilonewtons per meter.

Table 8.5. Statistical significances of regression coefficients

Variable	Calendar age	Maturity offset	Body height	Body mass	Total GJH score	Training volume
Body mass (kg)	0.18	0.15	0.12	0.14	0.08	0.41
Body fat (%)	0.16	0.13	0.19	0.33	0.21	0.28
Sub-max hop 2.0 Hz (kN/m)	0.65	0.63	0.42	0.64	0.54	0.08
Sub-max hop 2.2 Hz (kN/m)	0.79	0.68	0.89	0.19	0.83	0.18
Sub-max hop 2.5 Hz right (kN/m)	0.54	0.45	0.75	0.01	0.88	0.88
Sub-max hop 2.5 Hz left (kN/m)	0.74	0.84	0.56	0.05	0.66	0.99
Sub-max hop 3.0 Hz right (kN/m)	0.11	0.12	0.08	0.04	0.56	0.96
Sub-max hop 3.0 Hz left (kN/m)	0.96	0.98	0.83	0.04	0.74	0.96
Broad jump (cm)	0.85	0.82	0.98	0.83	0.25	0.15
Broad hop right (cm)	0.41	0.39	0.60	0.39	0.06	0.17
Broad hop left (cm)	0.89	0.77	0.36	0.30	0.06	0.17
Triple broad jump (cm)	0.70	0.74	0.74	0.82	0.19	0.57
Triple broad hop right (cm)	0.28	0.44	0.94	0.63	0.01	0.02
Triple broad hop left (cm)	0.67	0.72	0.95	0.66	0.03	0.19
Reactive strength index (m/s)	0.31	0.37	0.49	0.52	0.14	0.76

GJH = generalized joint hypermobility; Sub-max = sub-maximal; Hz: Hertz; kN/m = kilonewtons per meter.

Table 8.6. Eta-squared of regression coefficients

Variable	Calendar age	Maturity offset	Body height	Body mass	Total GJH score	Training volume
Body mass (kg)	0.08	0.09	0.10	0.09	0.14	0.03
Body fat (%)	0.09	0.11	0.08	0.04	0.07	0.05
Sub-max hop 2.0 Hz (kN/m)	0.01	0.01	0.03	0.01	0.02	0.15
Sub-max hop 2.2 Hz (kN/m)	0.00	0.01	0.00	0.09	0.00	0.10
Sub-max hop 2.5 Hz right (kN/m)	0.02	0.02	0.00	0.31	0.00	0.00
Sub-max hop 2.5 Hz left (kN/m)	0.01	0.00	0.02	0.19	0.01	0.00
Sub-max hop 3.0 Hz right (kN/m)	0.09	0.08	0.11	0.17	0.01	0.00
Sub-max hop 3.0 Hz left (kN/m)	0.00	0.00	0.00	0.20	0.01	0.00
Broad jump (cm)	0.00	0.00	0.00	0.00	0.07	0.11
Broad hop right (cm)	0.03	0.04	0.01	0.03	0.19	0.09
Broad hop left (cm)	0.00	0.00	0.03	0.04	0.16	0.08
Triple broad jump (cm)	0.01	0.01	0.01	0.00	0.10	0.02
Triple broad hop right (cm)	0.03	0.02	0.00	0.01	0.21	0.16
Triple broad hop left (cm)	0.01	0.01	0.00	0.01	0.23	0.08
Reactive strength index (m/s)	0.06	0.04	0.03	0.02	0.12	0.01

GJH = generalized joint hypermobility; Sub-max = sub-maximal; Hz: Hertz; kN/m = kilonewtons per meter.

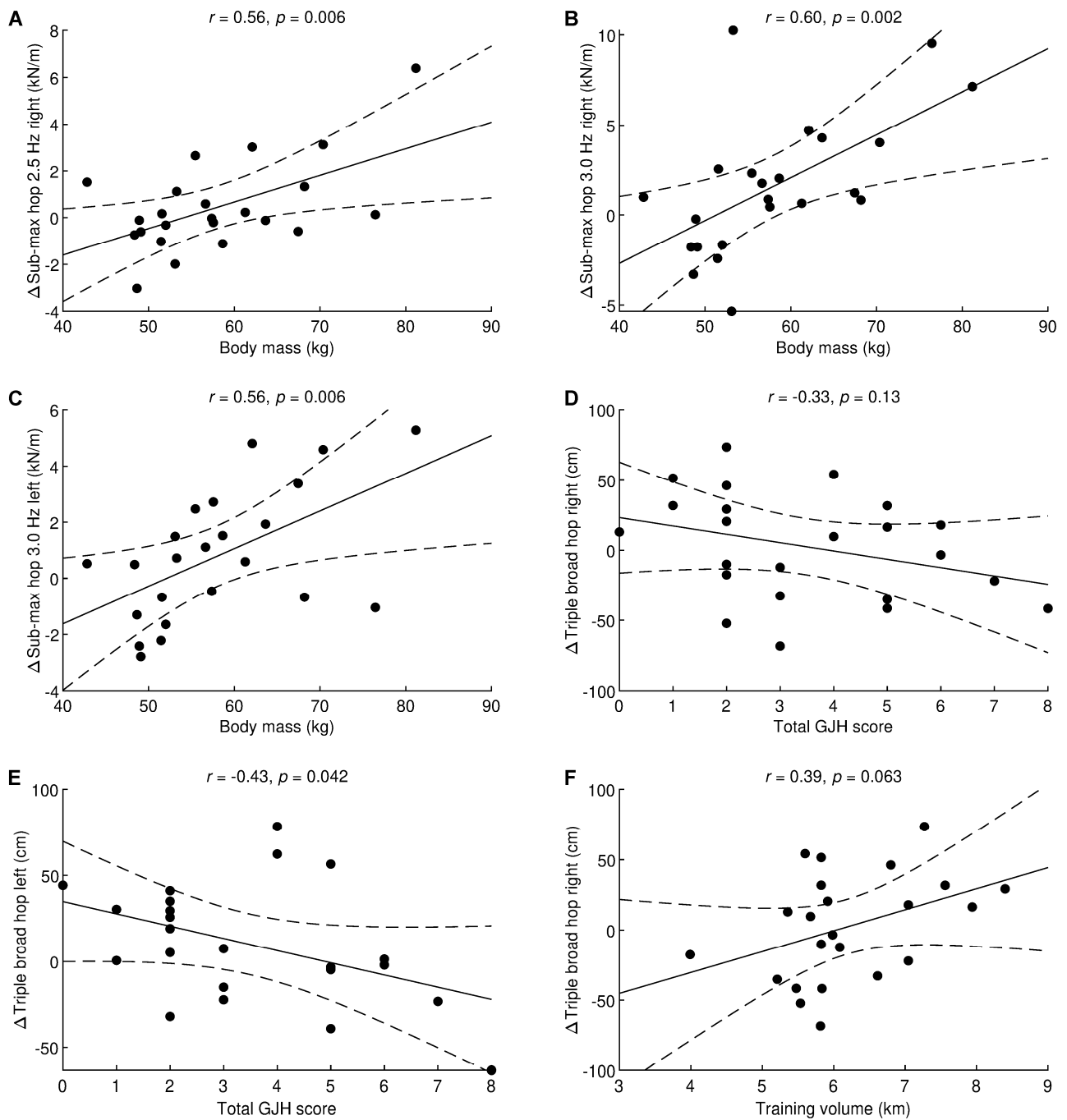


Figure 8.1. Correlation analysis between changes in dependent variables and body mass, total generalized joint hypermobility (GJH) score, and training volume.

r = Pearson's correlation coefficient; p = statistical significance of the correlation coefficient; Δ = difference between post-test versus pre-test; Sub-max = sub-maximal; Hz = Hertz. Dashed lines denote a 95% confidence interval.

8.5 DISCUSSION

The primary aim of this study was to explore the effect of an eight-week horizontal plyometric training program on SSC jumping and hopping in post-PHV female volleyball players. The main findings of the current study demonstrated that an eight-week plyometric training program improved absolute leg stiffness at the preferred frequency (2.5 Hz, left leg) in post-PHV female volleyball players. To our knowledge this is the first intervention study to explore the effect of horizontal plyometric training on leg stiffness during vertical unilateral hopping and on explosive horizontal jumping and hopping ability using a novel protocol in post-PHV female volleyball players. The second aim was to assess the influence of training, age, body size, and tissue related (GJH) moderating variables on plyometric training. Regarding the interaction of plyometric responses and moderating variables, body mass moderated the effect of plyometric training on the largest number of parameters, specifically, vertical sub-maximal hopping at 2.5 Hz on the right leg, and at 3.0 Hz on the left and right leg. This is the first study to assess the influence training, age, body size, and tissue related (GJH) variables on such plyometric training in volleyball players. The results of the present study indicate that a sufficient training stimulus was provided to improve leg stiffness at the preferred hopping frequency in youth, but not for horizontal jumping and hopping ability or RSI. Lastly, body mass and not age, maturity, training volume or GJH served as the best moderator of horizontal plyometric training.

8.5.1 Training effect

The intervention in the current study consisted of horizontally oriented plyometric exercises that involved an SSC and were reactive in nature. The ability to rebound off the ground can be aided by leg stiffness, a component of effective SSC function (Radnor et al., 2017). Leg stiffness describes the ability to attenuate an applied force during deformation of the leg, where an optimal level of stiffness allows a large force to be attenuated over a shorter range of motion (McMahon and Cheng, 1990). This training intervention led to a significant increase in absolute leg stiffness during vertical bilateral hopping at 2.0 Hz, 2.2 Hz, and vertical unilateral hopping at 2.5 Hz on the left leg. The medium intervention effect for sub-maximal hopping at 2.0 Hz (9.5%) and 2.5 Hz (4.4%) on the left leg exceeds the within subject error (2.0 Hz: 8.23%, 2.5 Hz: 3.89%) of Chapter 3 and can thus be considered

clinically significant. Furthermore, the small degree of intervention effect for sub-maximal hopping at 2.2 Hz (6.8%) did not exceed the within subject error (7.25%) of Chapter 3 and is not considered clinically significant. Furthermore, the significant improvement in leg stiffness during vertical unilateral hopping at 2.5 Hz on the left and not the right leg agrees with Chapter 3, in that the left leg represented the dominant leg for most participants, as determined by the stance leg during kicking (Waxman et al., 2018). The increased reliability of left leg vertical hopping (Chapter 3) might have influenced why significant results were demonstrated on that leg in the current investigation.

Changes larger than the within subject error indicate that plyometric training can induce changes in leg stiffness over and above what would be expected by natural development (Radnor et al., 2017). The findings of the present study are relevant in demonstrating that a horizontal plyometric stimulus can also lead to improvement in vertical outcomes other than vertical countermovement jumps in post-PHV female athletes (Talukdar et al., 2022), in this case, absolute leg stiffness during unilateral vertical sub-maximal hopping. In addition to body mass and maturity, muscle pre-activation and the stretch-reflex response of the leg extensors, are the major predictors of absolute leg stiffness in youth, explaining approximately 97% of the variance in leg stiffness (Oliver and Smith, 2010). In the present study, where maturity did not moderate change in leg stiffness and body mass did, increased leg stiffness observed in youth female volleyball players after the plyometric training program could also presumably be explained by muscle activity (Oliver and Smith, 2010).

The current study suggests that post-PHV female volleyball players can improve leg stiffness after a plyometric training program. However, the effect of plyometric training on leg stiffness in post-PHV female athletes overall still requires further investigation. Moreover, the effect of plyometric training on leg stiffness in pre-PHV or circa-PHV girls also remains unclear due to a paucity of studies. It is for this reason studies in boys are used to help elucidate these effects. For example, improvement in absolute and relative leg stiffness in 12- and 15-year-old male physical education students have been demonstrated during vertical bilateral hopping at 2.5 Hz after a four-week plyometric training program. The same study revealed that nine-year-old physical education students did not demonstrate improvements in

leg stiffness (Lloyd et al., 2012a). Similar investigations have not been conducted in girls, therefore, further studies in youth female athletes are needed to affirm the effect of plyometric training on leg stiffness in general, as well as to ascertain the effect of plyometric training on leg stiffness in youth female athletes across maturation in comparison to a control group to further discern the training effect from the natural development effect.

The present study did not reveal significant increases in RSI after a plyometric training intervention. This finding indicates that while potential benefits for SSC behavior could be expected due to increased leg stiffness, other aspects of SSC performance were not improved. More specifically, the RSI parameter in our study derived from the drop jump test, is used to assess an athlete's ability to produce force rapidly and higher values of the RSI are associated with the effective use of muscle elasticity and neuromuscular control of working muscles (Flanagan and Comyns, 2008, Jarvis et al., 2022). Observation of the discrepancy between training induced effects in absolute leg stiffness and RSI indirectly supports a previous suggestion, that RSI has only a limited amount of variance with leg stiffness (Lloyd et al., 2011a). Absence of benefit in the case of RSI agrees with previous studies in eight-year-old female gymnasts after an eight-week plyometric training intervention (Bogdanis et al., 2019), and in eight-year-old female gymnasts after a combined eight-week plyometric, muscular strength, muscular endurance, movement competency and dynamic stabilization training program (Moeskops et al., 2018a). However, our finding regarding RSI is not commensurate with findings of a recent systematic review with meta-analysis by Ramirez-Campillo et al. (2023a), which revealed significant gains in RSI after plyometric training programs in males and females under 18 years old. This systematic review with meta-analysis by Ramirez-Campillo et al. (2023a), also did not find sex or maturational status to be a significant moderator of plyometric training effect on RSI. Moreover, another recent systematic review with meta-analysis on healthy individuals across the lifespan revealed that plyometric jump training was effective (Hedges' $g = 0.54$, small effect) at improving leg stiffness (Ramirez-Campillo et al., 2023b). We assume that one of the reasons why positive changes of the RSI were not observed in our study were the differences between movement content of the current investigation's horizontal plyometric program exercises, and vertical nature of the drop jump test. As it is generally accepted that RSI is an important measure of SSC capability in youth athletes related to both athletic performance (Flanagan and Comyns, 2008, Jarvis et al., 2022,

Ramirez-Campillo et al., 2018a) and injury prevention (Raschner et al., 2012, Toumi et al., 2006) and considering that the natural development of RSI differs in boys and girls (Laffaye et al., 2016, De Ste Croix et al., 2021, Lehnert et al., 2022), existing ambiguities concerning potential benefits of plyometric training on RSI in youth female athletes should be clarified. Therefore, more investigations into different lengths and types of plyometric training interventions in girls are required to elucidate this theory. It must also be considered that the sport and training experience level and sex of participants are important, given that improvements may be more difficult to induce in girls or more athletically experienced individuals (Asadi et al., 2017a, Moran et al., 2018a, Faigenbaum et al., 2002, Lehnert et al., 2022) and that in youth (age < 18 years) smaller training induced changes can be expected compared to adults (Ramirez-Campillo et al., 2023b).

Horizontal plyometric training did not induce a significant improvement in any of the horizontal jumps or hops. Despite the 2.4% decrease in the broad jump, this decrease was not considered significant, given that it did not exceed the previously stated within subject error of 2.82% from Chapter 3. It is difficult to explain with certainty as to why there was no significant improvement in horizontal jump and hop movements. One explanation is that horizontally directed plyometric exercises require the body to be projected into the air and across the ground, which may require a higher level of coordination to execute (Ramirez-Campillo et al., 2015b). This might be especially true when considering the reality of teaching exercises to young athletes. Horizontally directed plyometric exercises require a higher level of coordination compared to vertically oriented plyometric exercises (Ramirez-Campillo et al., 2023a, Fukashiro et al., 2005). Given that intensity is a vital consideration for plyometric training effectiveness (Ramirez-Campillo et al., 2023a, Brauner et al., 2014, Maloney et al., 2015), it is possible that while learning to coordinate these movements, the ability to perform these exercises maximally was affected.

Significant improvements in the broad jump have been demonstrated in girls from various sports and similar age range to players in the current study (age 13–16). For example, improvements were noted after a seven-week horizontal jump training intervention (Talukdar et al., 2022), after both eight-week bilateral and unilateral plyometric interventions (Kong,

2018), after both sagittal plane and frontal plane six-week plyometric interventions (McCormick et al., 2016), after a 10-month combined movement competency, strength, ballistic, plyometric and speed training program (Moeskops et al., 2022a), and after an eight-week plyometric, speed and strength training intervention (Marta et al., 2014). The disagreement with the literature also applies to horizontal single and triple hopping where fifteen-year-old soccer, basketball and volleyball players were able to significantly improve their single leg hop distance after a six-week neuromuscular training program (Myer et al., 2005). Similarly, 13–18-year-old athletic girls from various sports significantly improved in single leg triple hop distance, after a six-week combined, jumping, plyometric, speed, endurance, agility training program (Noyes and Barber-Westin, 2015). However, differences between the current study and those in the literature are noted for movement orientation, analysis method (McCormick et al., 2016, Kong, 2018), intervention length (McCormick et al., 2016, Moeskops et al., 2022a), training content (Marta et al., 2014, Moeskops et al., 2022a), and sport background (McCormick et al., 2016, Marta et al., 2014, Moeskops et al., 2022b). These methodological differences revealed throughout the literature make clarifying the effect of plyometric training on the broad jump test difficult. The existence of the external moderators noted does not allow for clarity as to the effect of plyometric training on horizontal jumping and hopping in youth female athletes. This uncertainty is confirmed due to the findings of a recent systematic review and meta-analysis, where small significant effect sizes ($g = 0.42-0.56$, small to moderate effects) were found for the effect of plyometric training on horizontal jump distance (Ramirez-Campillo et al., 2023a).

8.5.2 Effect of moderators

The adaptive response to plyometric training may be influenced by various moderators (Ramirez-Campillo et al., 2023a, Moran et al., 2018a). The present study sought to determine the influence of several moderators on plyometric training. However, the present study discovered that only body mass and total GJH combined with training volume had a moderating effect on plyometric training in post-PHV female volleyball players. Therefore, there remains uncertainty regarding the effect of moderators on plyometric training in girls.

The present study discovered that in a sample of post-PHV volleyball girls, there were no moderating effects of age, height or maturity offset. These findings agree with a meta-analysis by Moran et al. (2018a) who demonstrated that older, taller and heavier girls adapted to plyometric training to a lesser extent compared to younger, lighter and shorter girls. In the study by Moran et al. (2018a), which used a median split analysis, girls above age 15 were considered older. The girls in the present study were 13.8 years old, initially suggesting they should share similar characteristics (similar moderating effect of age on plyometric training) to the girls below the median in the study by Moran et al. (2018a). However, this was not the case. Furthermore, when compared to girls in Moran et al. (2018a), the girls of the present study were taller than the median height of the participants in Moran et al. (2018a). This would suggest they resemble the older girls of Moran et al. (2018a) and thus the reason for the lack of moderating effect of height or age in the present study.

Chronological age can be misleading as a moderator variable, given that many changes during adolescence occur due to increased biological age (Lloyd et al., 2016a). However, in the study by Moran et al. (2018a), there was no analysis completed regarding the moderating effect of maturation on plyometric training (Moran et al., 2018a). This is not surprising given the scarcity of studies in girls where researchers have assessed maturation during plyometric training interventions. Currently there is no consensus regarding how girls of different maturity status adapt to plyometric training. For instance, in a recent systematic review with meta-analysis, it was shown that there is a paucity of studies in young girls where the moderating effect of maturation has been assessed during plyometric training interventions (Ramirez-Campillo et al., 2023a). Additional studies are required in youth female athletes where researchers assess maturation so a consensus can be generated regarding the moderating effect of maturation on plyometric training. It is also suggested that additional moderator analysis, other than anthropometric variables, be investigated by researchers which assess the functional qualities of the neuromuscular and musculoskeletal systems (Beerse and Wu, 2022).

8.5.2.1 Effect of training volume

The present study revealed that training volume moderated one dependent variable but only when combined with the moderating effect of total GJH score. Specifically, a higher training volume and a lower total GJH score led to a higher value of triple broad hop on the right leg. The absence of significant effect of training volume may be attributed to the attendance criteria of 75% or more. This criterion limited the variability in the training volume across the participants (Lloyd et al., 2012a).

In the present study, training volume did not significantly moderate the effect of plyometric training on RSI. This finding is in line with findings of a previous systematic review with meta-analysis demonstrating that training volume in the form of number of weeks, total jumps, and total training sessions did not significantly moderate the effect of plyometric training on RSI (Ramirez-Campillo et al., 2023a) and vertical countermovement jumps in youth under 18 years old (Ramirez-Campillo et al., 2023a). However, in another recent systematic review with meta-analysis, the authors noted that three sessions per week, more than seven weeks and more than 14 sessions, was a more effective dose to improve RSI in healthy people across the lifespan than under three weekly sessions, under 14 total sessions and under 14-weeks of training (Ramirez-Campillo et al., 2023b). Therefore, there may be differences between how youth under 18 years old respond to plyometric training compared to individuals across the lifespan.

Despite the significant increase in absolute leg stiffness during bilateral hopping at 2.0 Hz and left leg hopping at 2.5 Hz, training volume did not significantly moderate the effect of plyometric training on absolute leg stiffness. Stiffness in healthy individuals across the lifespan was shown to increase due to lower plyometric training volume, specifically, under 16 sessions, under three sets, and equal to or under 2 sessions per week (Moran et al., 2023). This relationship between training and stiffness differs from that of training volume and RSI for healthy individuals across the lifespan. It is likely that different expressions of the SSC like stiffness and RSI, have dissimilar dose-adaptation relationships. More studies investigating the effects of training volume with different numbers of jumps, weekly

frequency, total sessions, and number of training weeks in the context of growth and maturation are required to clarify this idea.

8.5.2.2 Effect of body mass

Correlation analysis was used to unveil the relationship between changes in each dependent variable and body mass at pre-test. Change in absolute leg stiffness during right leg vertical sub-maximal hopping at 2.5 Hz ($r = 0.56$) and 3.0 Hz ($r = 0.60$) and left leg vertical hopping at 3.0 Hz ($r = 0.56$) were correlated to body mass at pre-test. These findings indicate that when evaluating the effect of plyometric training on leg stiffness at preferred vertical hopping frequencies (2.5 Hz) and faster hopping frequencies (3.0 Hz), increased body mass at pre-test moderates plyometric training to produce higher leg stiffness. During the reactive hops, the entire body mass must be projected into the air against gravity after rebounding off the ground. This rebounding process is aided by increased amounts of leg stiffness, which helps attenuate large ground reaction forces without a large deformation (Pedley et al., 2020, Lloyd et al., 2009). Specifically, if leg stiffness does not increase with a larger mass, then the body will display a diminished ability to consistently control the landing forces and maintain an appropriate level of deformation to meet athletic task demands (Pedley et al., 2020, Lloyd et al., 2009, Meyers et al., 2016).

Athletic tasks executed in sport impose mechanical loading which leads to stiffness changes in youth (Waugh et al., 2012). This training and sport related loading can also be accompanied by chronic mechanical loading from growth and maturation related body mass increases, which also lead to increased stiffness in young people (Waugh et al., 2012, Chalatzoglidis et al., 2021). This notion is supported by literature demonstrating that body mass is a primary contributor to absolute leg stiffness in 11–12-year-old boys, explaining from 61.7% to 75.8% of the variation during vertical hopping at preferred frequencies (Oliver and Smith, 2010, Lloyd et al., 2011a). Other significant contributors include extensor muscle activity upon ground contact (Oliver and Smith, 2010), which can be improved from training and sport related loading (Waugh et al., 2012). However, it is also known that girls increase their body fat mass to a higher degree compared to boys throughout childhood and adolescence (Naughton et al., 2000). This body composition change can negatively affect relative force

production and impulse during reactive movements like jumping (Emmonds et al., 2017). This previous finding has been demonstrated in a meta-analysis in which heavier girls that were taller and older, adapted to plyometric training to a lesser degree compared to lighter, younger and shorter girls (Moran et al., 2018a). Thus, to offset the negative effects of maturity related increases in fat mass, appropriate training, and sport related loading, like plyometric training and strength training, may help increase extensor muscle activity and thus stiffness (Ramirez-Campillo et al., 2023a, Moran et al., 2023). Previous studies in girls have not investigated the moderating effect of body mass on the change in performance due to a plyometric training program. There remains much variation unexplained in girls concerning SSC performance (Ramirez-Campillo et al., 2023a). Therefore, SSC jump and hop performance is not solely affected by body mass but is affected by maturation related neuromuscular factors that aid in controlling landing forces to help produce a forceful subsequent propulsive phase (Meylan et al., 2014a).

8.5.2.3 Effect of age and maturity

Correlation analysis did not reveal a significant relationship between the change in any of the performance variables and maturity offset or age. Nevertheless, it must be considered that the present study did not evaluate girls across maturation, and instead evaluated post-PHV girls only. The present study's results thus indicate that for girls between 11.8–15.8, maturity timing and age did not significantly influence the effect of plyometric training on jumping and hopping ability. There is a previous meta-analysis that discovered that the effect of plyometric training on jumping performance was smaller among older (above 15 years), taller (above 163 cm) and heavier girls (above 54 kg) compared to younger, shorter and lighter girls (Moran et al., 2018a). Moreover, in a systematic review with meta-analysis in healthy individuals across the lifespan, it was discovered that RSI improvements were better in adults compared to youth after plyometric training (Ramirez-Campillo et al., 2023b). However, the populations investigated in Moran et al. (2018a) were girls of a similar and older age to the present study, whereas Ramirez-Campillo et al. (2023b) investigated healthy individuals across the lifespan. Direct comparisons between these previous studies and the present study are difficult. It has been suggested that the SSC develops non-linearly with age (Radnor et al., 2017), a finding which has been discovered for RSI in 8–13-year-old figure skating girls (Lehnert et al., 2022), 11–20-year-old girls (Laffaye et al., 2016), and 7–16-year-old boys

(Lloyd et al., 2011b). Furthermore, leg stiffness in girls has also been shown to develop non-linearly with age although, the significant increases occurred within age ranges not commensurate with those of the present study (Laffaye et al., 2016). Given the lack of moderating effects of age and maturation, it could be that most participants in the present study were of an age in which plyometric training is not moderated by age or maturation. Overall, this study suggests that plyometric training may be an effective method for improving leg stiffness in post-PHV female athletes, regardless of their age and maturity status. Further research is needed to confirm age and maturity ranges which influence jumping and hopping ability in girls. These studies should include pre-PHV participants and girls under 11 years old.

8.5.2.4 Effect of hypermobility

The present study revealed that total GJH score moderated the triple broad hop right and the triple broad hop left. Subsequent correlation analysis was performed to determine the relationship between changes in the triple broad hops after the plyometric training program. The correlation analysis revealed that total GJH score only moderated the plyometric training effect on left leg triple broad hop performance, whereas total GJH score, and training volume together significantly moderated the plyometric training effect on right leg triple broad hop performance. Given the negative correlations, this finding indicates that a lower total GJH score is associated with a higher ability to perform repetitive horizontal hops. Increased GJH may negatively affect force transmission and tissue elasticity, potentially leading to excessive tissue strain and joint excursions, thus causing a decreased ability to control landing forces through an appropriate deformation (Simmonds, 2022). Under these conditions, the ability to rebound effectively off the ground is diminished (Getchell and Robertson, 1989, Tveter and Holm, 2010). Comparisons to previous literature for this parameter are not possible since there are no studies that have investigated the moderating effect of total GJH score on plyometric training in girls. Thus, further investigations are required to clarify this moderating effect of total GJH score on plyometric training in girls, and the effect of total GJH score overall on physical qualities like speed, power, strength, and stiffness in girls.

8.6 LIMITATIONS

The results of the present study must be interpreted with caution due to a few limitations. The first limitation was that many participants were excluded due to low attendance rates, or missing data. This removal resulted in a final sample size of 23, which was less than the required sample size of 26 obtained from the power analysis, reducing the statistical power to observe a true effect (Turner et al., 2015). The second limitation is that only post-PHV girls were evaluated. This resulted in unequal representation of participants of different chronological and biological ages. Therefore, we recommend replicating this study using pre-PHV participants and comparing them to post-PHV participants. Lastly, considering the elevated level of coordination required for horizontal movements and the practicality of teaching exercises to youth, it is our recommendation to give a longer familiarization period for horizontally directed plyometric exercises. The present investigation used a minimal dose of intervention exercises during the one-week familiarization. Upon reflection, this period and dose is deemed insufficient to properly familiarize participants to horizontal plyometric exercises. Thus, two weeks of familiarization before executing an eight-week training period would presumably give a more appropriate plyometric training dose to elicit improvement in horizontal jumping and hopping exercises and potentially RSI.

8.7 CONCLUSION

The present study concludes that eight weeks of horizontal plyometric training can improve unilateral absolute leg stiffness in post-PHV female volleyball players, and this training effect can be moderated by body mass. Furthermore, the training effect on triple broad hopping performance on the right leg can be moderated by combined training volume with total generalized joint hypermobility. This finding suggests that leg stiffness, reactive strength index, single and triple horizontal jumping and hopping may require different training dosages in post-PHV female volleyball players. Future recommendations include utilizing a longer familiarization period, a longer intervention period, and investigations that include pre-PHV participants.

8.8 PRACTICAL RECOMMENDATIONS

An eight-week horizontal plyometric training intervention increases absolute leg stiffness in post-PHV female volleyball players and that out of the observed moderators, only initial body mass of the players may influence the training effect. Concerning training induced changes, it seems that increases in leg stiffness indicate positive changes from both performance related and injury-prevention related point of view. However, no other observed parameter was improved after the intervention. For practitioners, it must be stressed that the results of the present study should be interpreted with caution, as specific programming parameters (e.g., horizontal plyometric exercises and their progression), program duration and volume, were applied to a specific group of post-PHV female volleyball players. Moreover, results of the study, in some cases, contradict the findings regarding studies with girls of similar characteristics. Therefore, further investigation is needed in this field to provide practitioners with valid plyometric training recommendations.

CHAPTER 9. GENERAL DISCUSSION

9.1 SUMMARY AND CONCLUSION

The overall aim of the current thesis was to investigate the rebounding ability of girls by examining the maturity and training-related differences in global stiffness during sub-maximal hopping and sprinting. This aim was first addressed by reviewing the global stiffness behavior of the musculoskeletal system throughout childhood and adolescence, examining how stiffness is regulated, and reviewing how global measures of stiffness respond to various training methods. This review showed that absolute leg stiffness experiences a non-linear increase throughout childhood and adolescence (Laffaye et al., 2016, Lehnert et al., 2020, Moeskops et al., 2020). Conversely, relative leg stiffness increases linearly throughout childhood, then experiences a plateau (Laffaye et al., 2016, Lehnert et al., 2020). Childhood stiffness development mechanisms are reported to favour tendon material changes (i.e., Young's modulus), and improvements in neural regulation (e.g., improved muscle preactivation), while adolescent mechanisms favour structural developments such as tendon dimensional changes (e.g., tendon cross-sectional area). Achieving training-related improvements using combined training (De Ste Croix et al., 2018) have been successful in adolescent girls but less successful or unclear during childhood (Katsikari et al., 2020, Moeskops et al., 2022a) (Chapter 2).

This thesis primarily quantified leg stiffness during sub-maximal hopping, chosen for its energy efficiency, high force-to-deformation ratio, and practicality when using a mobile contact mat (Maloney and Fletcher, 2018, Maloney et al., 2015). It was essential to establish inter-day reliability data for unilateral and bilateral sub-maximal hopping at various frequencies on the contact mat and determine the most suitable leg stiffness calculation method. Reliability was confirmed at all specified frequencies, except for 2.5 Hz on the non-dominant leg. Notably, sub-maximal hopping at 2.5 Hz on the dominant leg ($CV\% = 3.89\%$), using all available contacts, was the most reliable condition and calculation method, respectively. These findings indicated that training-related improvements in leg stiffness during sub-maximal hopping on the dominant leg exceeding 3.89% would be considered clinically significant (Chapter 3).

The inter-day reliability of horizontal jumping (two-foot take-off) and hopping (one foot take-off) distance of two maturity groups (PRE + EPUB, LPUB) was examined. Acceptable reliability for girls of both maturity groups for all jumping and hopping protocols was demonstrated. Jumping tasks were more reliable than hopping tasks, as noted by the lower CVs. However, it was recommended that when testing horizontal jump and hop distance using the protocols in Chapter 4, two familiarization sessions should be administered to improve testing accuracy (Chapter 4). Furthermore, caution should be exercised when testing triple broad hop distance in less mature girls due to the larger CV ($CV > 7\%$) values accompanied by larger CI and larger SD of the change in mean, compared to the more mature group ($CV < 4\%$).

The literature revealed several gaps regarding the natural development of stiffness in girls, with studies focusing on limited age ranges and various stiffness forms. Notably, leg stiffness was not assessed during sub-maximal or unilateral sub-maximal hopping across different maturity stages. Chapter 5 highlighted significant differences in all stiffness variables during sprinting between PRE and MPUB stages, with no differences between other maturity group pairings. Additionally, maturity-related differences in sprint speed and spatio-temporal variables were found, particularly for speed and step length.

Chapter 6 examined how absolute and relative leg stiffness varied among girls of different maturity status during unilateral vertical sub-maximal hopping. A linear development trend for absolute leg stiffness and non-linear development for relative leg stiffness was discovered. These findings indicate that maturity has a substantial influence on leg stiffness. Furthermore, despite the distinct mechanisms underlying natural leg stiffness development in children and adolescents (Radnor et al., 2017), a comparable level of training-induced absolute leg stiffness improvement may be necessary for children and adolescents alike. Chapter 6 also showed that absolute and relative leg stiffness along with anthropometric variables (body mass, body fat%, leg length), explained 48.4% of 20-meter sprint time in girls.

The findings of Chapter 7 indicated that training related improvements in leg stiffness occurred after plyometric training and not linear sprint training relative to a control group. More specifically, there was a significant group x time interaction for leg stiffness during hopping on the dominant leg at 2.5 Hz. This significant improvement (4.2%) exceeded the established within-subject error from Chapter 3 (CV = 3.89%), indicating a clinically significant improvement (Turner et al., 2015). It was suggested that plyometric training caused greater vertical projection of the body, with longer flight times along with higher vertical ground reaction forces and larger musculotendinous stretch-loading upon subsequent ground contact (Chapter 7). A significant effect of late pubertal maturity status on leg stiffness in Chapter 7, led to further exploration of training-related improvements in more mature girls (post-PHV). Additionally, other participant characteristic-related moderators (e.g., body mass) and training-related moderators (e.g., training volume) were assessed for how they influenced the plyometric training effect on several dependent variables. Significant improvements were observed in post-PHV girls for vertical bilateral hopping at 2.0 Hz, vertical bilateral hopping at 2.2 Hz, and vertical unilateral hopping at 2.5 Hz on the left (dominant) leg. The intervention effect for sub-maximal hopping at 2.0 Hz (9.5%) and 2.5 Hz (4.4%) on the left leg exceeded the within-subject error (2.0 Hz: 8.23%, 2.5 Hz: 3.89%). Furthermore, body mass at pre-testing served as a significant moderator of plyometric training for three leg stiffness conditions. These conditions were, hopping at 2.5 Hz on the right leg, and hopping at 3.0 Hz on the right and left legs. Moreover, plyometric training's impact on triple broad hopping performance on the right leg was affected by both training volume and total generalized joint hypermobility (Smits-Engelsman et al., 2011). Essentially, a higher training volume and less excessive joint range of motion together led to higher triple broad hop scores. Therefore, between leg stiffness measures and horizontal jump and hop measures, post-PHV female volleyball players may need unique training variables to elicit improvements in each (Chapter 8).

In addition to comparing training-related improvements from Chapter 7 and 8 to the within-subject error from Chapter 3, training-related improvements can also be compared to previous literature and the maturity-related differences in leg stiffness during sub-maximal

hopping in Chapter 6. Overall, the improvement due to training for leg stiffness during sub-maximal hopping on the dominant leg ranged from 4.2% to 4.4% (Chapter 7 and 8), with a Hedges' g effect size ranging from 0.23 (95% CI = -0.36, 0.82, small effect) to 0.28 (95% CI = -0.31, 0.86, small effect). Additionally, the Cohen's d effect size ranged from 0.22 to 0.32 (small effect). A meta-analysis on the effects of plyometric training on stiffness in healthy individuals of all ages (Moran et al., 2023) reported that plyometric training for both global and intrinsic stiffness, showed small effect sizes overall ($d = 0.33$, 95% CI = 0.07, 0.60). Untrained individuals showed small effect sizes ($d = 0.46$, 95% CI = 0.08, 0.84), while trained individuals showed smaller non-significant effect sizes ($d = 0.15$, 95% CI: -0.23, 0.53, trivial effect). However, global forms of absolute stiffness reported in the meta-analysis exhibited small effect sizes ($d = 0.21$, 95% CI = -0.03, 0.45) that aligned with those of the present thesis. Therefore, improvements in leg stiffness due to plyometric training are expected to be small among youth female athletes.

The small effect sizes suggest that while plyometric training improves leg stiffness, the extent is limited. In Chapter 6, absolute leg stiffness differences (Hedges' g) were 1.27 between EPUBPRE and MPUB and between MPUB and LPUB, while relative leg stiffness differences were 0.29 and 0.16, respectively. The much larger effect sizes for maturity-related differences indicate that natural growth and development have a greater impact on leg stiffness than training alone. For youth female athletes, training programs should consider the minor improvements from plyometric training and recognize the significant role of maturation in developing leg stiffness. Coaches and trainers should adjust their expectations and training protocols, focusing on long-term development that includes both training and accommodating natural growth phases. Further studies could explore ways to enhance the effectiveness of training interventions or identify the optimal timing for such training relative to various stages of maturation. Below is a summary of the key findings from the thesis, which outlines original and significant findings regarding maturity-related leg stiffness behavior and training-related stiffness development in girls.

9.2 MAIN FINDINGS

Aim 1. Review the literature related to the global stiffness behavior of the musculoskeletal system, and how it develops according to maturity and training.

- Absolute leg stiffness increases non-linearly during childhood and adolescence, while relative leg stiffness rises linearly during childhood and then plateaus. The mechanisms behind stiffness development differ between childhood and adolescence.
- While strength and combined training methods have shown significant results, it is unclear if all methods are effective for girls at every maturity stage.
- Only one study examined the effect of plyometric training on stiffness in girls and the improvements were non-significant in 9-11-year-old girls.
- No studies involved the investigation of sprint training on stiffness in girls.

Aim 2. Assess the inter-day reliability of absolute and relative leg stiffness in girls during vertical sub-maximal hopping at various frequencies.

- Absolute and relative leg stiffness during sub-maximal hopping were deemed reliable at 2.0 Hz, 2.2 Hz, 2.5 HzD, 3.0 HzND, 3.0 HzD. The within-subject error for the sub-maximal hopping tests using the AC, AC5 and 10Hop stiffness calculation methods exhibited the following ranges: 2.0 Hz (8.23%-9.44%); 2.2 Hz (7.25%-9.29%); 2.5 HzND (4.35%-4.75%); 2.5 HzD (3.89%-4.82%); 3.0 HzND (5.48%-5.79%); 3.0 HzD (5.13%-7.19%). The most consistent hopping condition was hopping at 2.5 Hz on the dominant leg, while the least suitable was hopping at 2.5 Hz on the non-dominant leg. The most suitable calculation method was averaging all contacts.

Aim 3. Assess the inter-day reliability of horizontal jumping and hopping in girls of differing maturity status.

- Acceptable reliability was discovered in girls of varying maturity status during all horizontal jumping and hopping protocols outlined in Chapter 4. Jumping tasks (two-foot take-off) were more reliable than hopping tasks (one-foot take-off).

Aim 4. Examine the intra-day reliability of absolute and relative vertical and leg stiffness during a 20-meter sprint in girls of varying maturity stages.

- No significant pairwise differences were found for Kvert, Kleg, RelKvert, and RelKleg in RMANOVA. Despite CVs of 3.06-6.24% for Kvert and RelKvert, CVs for Kleg and RelKleg ranged from 11.37-15.46%.

Aim 5. Investigate the maturity-related differences in absolute and relative vertical and leg stiffness and sprint spatio-temporal variables during a 20-meter sprint in girls.

- The magnitude of difference for all stiffness variables during sprinting were large and significant between PRE and MPUB. These differences possessed Hedges' g effect sizes ranging from 1.51-1.64.
- There were significant differences between PRE and MPUB for speed ($g = 1.66$, 95% CI = 0.55, 2.76, $p < 0.01$) and SL ($g = 1.79$, 95% CI = 0.67, 2.92, $p < 0.01$, large effect) but not CT, SF, or FT.

Aim 6. Examine how absolute and relative leg stiffness differ among girls of varying maturity status during unilateral vertical sub-maximal hopping and their impact on sprint performance in young girls.

- The magnitude of difference in absolute leg stiffness during sub-maximal hopping was significant, large (ES), and similar between EPUBPRE and MPUB ($g = 1.27$, 95% CI = 0.81, 1.73) and MPUB compared to LPUB ($g = 1.27$, 95% CI = 0.85, 1.69).
- Relative leg stiffness only differed significantly between the least mature group (combined pre-pubertal and early pubertal) and most mature group (late pubertal) with a small Hedges' g effect size of 0.48 (95% CI = 0.16, 0.8)
- Absolute and relative leg stiffness during sub-maximal hopping, along with anthropometric variables (body mass, body fat%, leg length) explained 48.4% of 20-meter sprint time.

Aim 7. Examine the impact of horizontal plyometric training compared to linear sprint training on absolute and relative leg stiffness, and absolute and relative horizontal jumping and hopping ability in young girls.

- Horizontally oriented plyometric training can significantly improve leg stiffness on the dominant leg while sub-maximal hopping at 2.5 Hz, relative to a control group. The effect of training over time as noted by the beta coefficients, was higher for plyometric training compared to the sprint training.

- Late pubertal maturity status had a significant effect on absolute leg stiffness during all unilateral hopping tests.

Aim 8. Explore how horizontal plyometric training and key training moderators influence leg stiffness and horizontal jump and hop distance in post-PHV girls.

- Horizontally oriented plyometric training produced significant improvements in vertical bilateral hopping at 2.0 Hz ($p = 0.021$, $d = 0.50$, medium effect), vertical bilateral hopping at 2.2 Hz ($p = 0.049$, $d = 0.37$, small effect), and vertical unilateral hopping at 2.5 Hz left ($p = 0.032$, $d = 0.32$, small effect) in post-PHV girls.
- The intervention effect for sub-maximal hopping at 2.0 Hz (9.5%) and 2.5 Hz (4.4%) on the left leg exceeds the within subject error (2.0 Hz: 8.23%, 2.5 Hz: 3.89%) outlined in Chapter 3.
- The effect of plyometric training on leg stiffness is significantly influenced by body mass at pre-test.
- The effect of plyometric training on triple broad hopping performance on the right leg was influenced by training volume and total generalized joint hypermobility combined.

9.3 PRACTICAL APPLICATIONS

This thesis was intended to provide researchers and strength and conditioning practitioners with the background knowledge on the rebounding ability of athletic girls by investigating the maturity-related and training-related differences in leg stiffness during sub-maximal hopping and sprinting. Based on the findings of this thesis, the following practical applications are offered:

1. The findings of this thesis suggest that practitioners utilize unilateral vertical sub-maximal hopping at 2.5 Hz on the dominant leg to assess leg stiffness in girls. This frequency represents the most reliable condition due to the more favorable force to deformation ratio. From the findings of Chapter 3, this frequency can be used during unilateral sub-maximal hopping similar to how leg stiffness during bilateral sub-maximal hopping has been deemed reliable in youth (Lloyd et al., 2009). The within-subject error reported in Chapter 3 indicated the threshold above which training-

related changes were considered clinically significant for leg stiffness measured during sub-maximal hopping in girls. Moreover, the ‘all contacts’ stiffness calculation method is recommended. This calculation method maintains the integrity of the data set by excluding a limited number of hops.

2. The within subject error for BJ, SBHR, SBHL, TBJ, TBHR, TBHL ranged from 2.91% to 7.46% for the lesser mature group (PRE + EPUB) and 2.82% to 3.75% for the more mature group. From these findings it is recommended that more caution be exercised when interpreting horizontal jump and hop tests in less mature girls, especially for repetitive horizontal hopping. Therefore, the use of use two familiarization sessions prior to assessment is recommended to improve testing accuracy.
3. The comparable absolute leg stiffness differences across maturity stages suggest that active girls involved in sports with running and jumping may attribute these differences to distinct mechanisms during childhood versus adolescence, potentially influenced by activity factors.
4. Developmentally appropriate plyometric training programs that allow sufficient time to learn the relevant movements are recommended. Specifically, the use of a two-week intervention familiarization period for young girls and an intervention period lasting at least eight weeks but preferably longer, running sessions twice a week using fast-SSC exercises is preferred.

9.4 LIMITATIONS

There are several limitations to consider when interpreting the results of this thesis. These limitations are outlined below:

1. The reliance on a contact mat to measure leg stiffness prevents direct measurement of vertical ground reaction force which allows determination of the force to deformation ratio (Beerse and Wu, 2016). However, the portability and lower cost of a contact mat provides users with a practical option to measure leg stiffness.
2. One familiarization session may not have been sufficient to mitigate a learning effect in Chapter 4. Rather, two familiarization sessions are recommended when employing horizontal jump and hop tests using this study’s protocols. Notably, most of these tests

have not previously been assessed for reliability according to maturity status in young girls. The authors also submit that the focus on distance measurements alone, restricts the analysis, as it precludes the assessment of kinetic or kinematic determinants of horizontal jumping and hopping ability. However, the inclusion of these advanced analyses requires increased time and financial resources, which may not be practical or feasible for a broader range of practitioners.

3. The sample size in Chapter 4 did not allow for sufficient participants to be classified as mid-pubertal maturity status, which limited data informing the reliability of horizontal jumping and hopping in girls across of wider range of maturity stages. However, this study provides a foundation to future studies wishing to examine maturity-related differences in horizontal jumping and hopping distance in girls.
4. It is acknowledged that skeletal age assessments are viewed as the gold standard measure of biological maturation, these assessments were not available and were not practical given the thesis requirements. Maturity status measured throughout this thesis represented the current state of maturation at the time of measurement rather than the changes that occur over time (Lloyd et al., 2014b, Cumming et al., 2017). However, the results of this thesis address a gap in the literature where other researchers have not investigated the maturity-related developments in leg stiffness during sub-maximal hopping in girls using the predicted adult height method.
5. Chapter 5 did not include late pubertal girls or sprinting at a longer distance. A longer distance would allow late pubertal girls to reach maximum speed and thus permit their inclusion in the investigation. Chapter 5 was the first study to evaluate stiffness during sprinting in girls.
6. Chapter 6 did not evaluate leg stiffness differences between dominant and non-dominant legs or compare unilateral and bilateral hopping at the same frequency. Such data could reveal whether leg stiffness development varies by leg or between unilateral and bilateral tasks. However, the data provided allowed for valuable insight into the role of the dominant leg in leg stiffness development in girls.
7. In Chapter 7, the sample size, participant maturity characteristics and attendance did not permit grouping participants by maturity status. Despite using statistical controls, the absence of group assignment based on maturity status may still introduce confounding effects, potentially influencing the interpretation of the training

interventions' impact. However, to address these limitations, a robust and flexible statistical method was employed: the linear mixed-effects model. This method effectively accommodates these limitations by allowing the analysis of both fixed and random effects on the dependent variable. Additionally, a similar training effect for the same variable was demonstrated in the next chapter.

8. During the training intervention (Chapter 8), many participants were excluded due to low attendance rates, or missing data. This removal resulted in a reduction of the statistical power required to observe a true effect (Turner et al., 2015). Nonetheless, a similar training effect for the same variable was demonstrated in the previous chapter. Moreover, the researcher provided a fun, engaging environment for the participants during the training intervention.
9. Considering the elevated level of coordination required for horizontal movements and the practicality of teaching exercises to youth, it was determined that the 1-week familiarization period was insufficient to properly familiarize participants to horizontal plyometric exercises. However, no other researchers have administered a horizontal plyometric training intervention or a sprint training intervention that has targeted leg stiffness in girls.

9.5 FUTURE RESEARCH DIRECTIONS

Addressing these limitations can guide future research on maturity- and training-related differences in leg stiffness during sub-maximal hopping and sprinting in girls. Below are suggestions for future research:

1. Assess the inter-day reliability of leg stiffness during a variety of tasks including horizontal drop jumping, forwards hopping, and change of direction tasks not previously investigated in youth female athletes.
2. Explore the spatio-temporal and kinetic variables that determine horizontal jumping and hopping. Researchers have not made use of floor-level optical measurement devices to measure these variables or leg stiffness during horizontal tasks like triple broad jumping.
3. Compare the maturity-related differences of various SSC tasks like sub-maximal hopping, maximal hopping, vertical drop jumping and horizontal drop jumping.

Examining stiffness during these tasks longitudinally across maturation would be valuable to fully understand the impact of growth and maturation on stiffness measures in girls.

4. Investigate the specific neuromuscular mechanisms supporting the differences and changes in leg stiffness between different maturation stages to provide deeper insights into the natural development of leg stiffness and how to optimize leg stiffness training protocols.
5. Compare multiple stiffness training methods using a longitudinal design to investigate the time-course of training adaptations in stiffness.
6. Investigations of intrinsic stiffness along with global stiffness measures to investigate maturity-related and training-related changes in stiffness.

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APPENDIX A. AUT ETHICS APPROVAL

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

18 February 2021

Craig Harrison
Faculty of Health and Environmental Sciences

Dear Craig

Re Ethics Application: **19/434 Sprinting characteristics in youth female athletes across maturation**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC). Your ethics application has been approved for three years until 18 February 2024.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the [Auckland University of Technology Code of Conduct for Research](#) and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.

AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken. Please quote the application number and title on all future correspondence related to this project. For any enquiries, please contact ethics@aut.ac.nz. The forms mentioned above are available online through <http://www.aut.ac.nz/research/researchethics>

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: rsylvester34@hotmail.com

APPENDIX B. CZECH ETHICS APPROVAL



Fakulta
tělesné kultury

Vyjádření Etické komise FTK UP

Složení komise: doc. PhDr. Dana Štěrbová, Ph.D. – předsedkyně
Mgr. Ondřej Ješina, Ph.D.
Mgr. Michal Kudláček, Ph.D.
Mgr. Filip Neuls, Ph.D.
prof. Mgr. Erik Sigmund, Ph. D.
doc. Mgr. Zdeněk Svoboda, Ph. D.
Mgr. Jarmila Štěpánová, Ph.D.

Na základě žádosti ze dne **10. 03. 2023** byl projekt aplikovaného výzkumu

Autor /hlavní řešitel/: **Mgr. Ivana Hanzlíková, Ph.D.**

Spolupřešitelé: **prof. PaedDr. Michal Lehnert, Dr., MSc. Richard Sylveste**

s názvem **Porovnání efektu rychlostního a plyometrického tréninku na sportovní výkonnost a rizikové faktory poranění dolních končetin u dívek 7–15 let**

schválen Etickou komisí FTK UP pod jednacím číslem: **15 / 2023**
dne: **24. 3. 2023**

Etická komise FTK UP zhodnotila předložený projekt a **neshledala žádné rozpory** s platnými zásadami, předpisy a mezinárodními směnicemi pro výzkum zahrnující lidské účastníky.

Řešitelé projektu splnili podmínky nutné k získání souhlasu etické komise.

Univerzita Palackého v Olomouci
Fakulta tělesné kultury
Komise etická
třída Miru 117 | 771 11 Olomouc

za EK FTK UP
doc. PhDr. Dana Štěrbová, Ph.D.
předsedkyně

Fakulta tělesné kultury Univerzity Palackého v Olomouci
třída Miru 117 | 771 11 Olomouc | T: +420 585 636 009
www.ftk.upol.cz

APPENDIX C. COVID ETHICS- HOME INSTITUTION


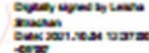

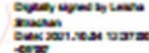

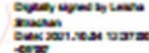


University of Manitoba

Request to Undertake Research Involving Human Participants at On- or Off-Campus Research Sites

Enter N/A on required fields if not applicable

Name of Principal Investigator(s) [first last] : Craig Harrison (PI) & Richard Sylvester (Student)							
Department: Sport and Recreation				Faculty: Health and Environmental Sciences			
Email address: craig@athletedevelopmentproject.com				Phone: +64272265181			
Will this research have direct contact with Indigenous communities? <input type="checkbox"/> Yes / <input checked="" type="checkbox"/> No (if the answer is "yes", please include a letter from the community confirming/affirming support of the continuation of research.							
Will this research involve international travel (i.e., travel outside Canada) <input type="checkbox"/> Yes / <input checked="" type="checkbox"/> No If the answer is "yes" please describe who is traveling, where they are traveling to/from, and for how long.							
Ethics Protocol Title: Sprinting characteristics in female athletes across maturation							
Ethics Protocol # : 19/434				If ethics has not yet been submitted, which REB office are you applying to? <input checked="" type="checkbox"/> Fort Garry <input type="checkbox"/> Bannatyne			
Does your informed consent form already explain the potential risk of COVID-19 with the wording provided by the REB? <input checked="" type="checkbox"/> Yes / <input type="checkbox"/> No If the answer is "no", an amendment to the REB is required.							
Date of activity: October 2021-February 2022							
Is the research site located at a U of M building? <input checked="" type="checkbox"/> Yes / <input type="checkbox"/> No (if the answer is no, please include a letter from the external organization confirming/affirming support of the research in their location)							
If not located at a U of M Building, Off-campus research site Active living centre multi purpose room 264 and track.							
Number of human participants involved: 100							
Name(s) of all graduate student(s), postdoc(s), research associate(s), and research technician(s) involved:							
Name [first last] Emily Morrison				Status Undergrad student			
Name [first last] Xinjing Song				Status Undergrad student			
Name [first last] Emily Saynavong				Status Undergrad student			
Name [first last]				Status			
Name [first last]				Status			
Please complete if research site is located at a U of M building only:							
Building ALC room 264 + track				Room Number ALC room 264 + track			
(Please indicate the total number of research personnel and human participants you will have in this room for each day and time slot)							
Days on Campus:	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
AM							
PM							
>4:30 PM							

Building ALC room 264 + track				Room Number ALC room 264 + track						
(Please indicate the total number of research personnel and human participants you will have in this room for each day and time slot)										
Days on Campus:	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday			
AM										
PM						3-5pm				
>4:30 PM										
Describe the nature and duration of the activity [max. 200 words]										
<p>The student will be conducting a research study on how to help youth female athletes bounce across the ground better when they run. The study will also assess jumping ability in the horizontal and vertical directions (not maximum). It will involve four 90 minute sessions.</p>										
Describe 1) why this research is <u>essential at this time</u> ; 2) why it cannot be done in a remote contactless manner; 3) what would be the impact of delay? [max. 200 words]										
<p>This study is essential at this time due the time limits of my PhD program. The student was displaced from New Zealand due to Covid-19, so there has already been a large delay. Any further delay will put the project in jeopardy permanently. This study cannot be done in a contactless manner because participants measuring themselves would not be a robust or reliable research practice.</p>										
Outline: i) the risks to the participants, research personnel, and community, ii) the nature and duration of the contact with human participants, and iii) the steps that will be taken to mitigate the risks (e.g., your plans for physical distancing, masking, sanitizing work spaces etc). [max. 400 words] See attached document										
<table border="0" style="width: 100%;"> <tr> <td style="width: 33%; vertical-align: top;"> Approvals:  <small>Digitally signed by Dr Craig Forshaw DN: c=CA, ou=University of Manitoba, ou=Faculty of Kinesiology, email=forshaw@umanitoba.ca, cn=Dr Craig Forshaw</small> <hr/> Principal Investigator Caryn Zinn <small>Digitally signed by Caryn Zinn DN: c=CA, ou=University of Manitoba, ou=Faculty of Kinesiology, email=zinn@umanitoba.ca, cn=Caryn Zinn</small> <hr/> ADR or Dean </td> <td style="width: 33%; vertical-align: top;"> Leisha Strachan  <small>Digitally signed by Leisha Strachan DN: c=CA, ou=University of Manitoba, ou=Faculty of Kinesiology, email=leisha.strachan@umanitoba.ca, cn=Leisha Strachan</small> <hr/> Department Head <hr/> Chair, COVID-19 Research Recovery Team </td> <td style="width: 33%; vertical-align: top; border: 1px solid black; padding: 5px;"> Note: When the department head, and ADR or Dean have signed, the form should be submitted to crsc_research@umanitoba.ca by Friday at 4:30pm. Otherwise, the request will be reviewed by CRRT at the next meeting. Processing time may take 1-2 weeks from receipt of the completed form. </td> </tr> </table>								Approvals:  <small>Digitally signed by Dr Craig Forshaw DN: c=CA, ou=University of Manitoba, ou=Faculty of Kinesiology, email=forshaw@umanitoba.ca, cn=Dr Craig Forshaw</small> <hr/> Principal Investigator Caryn Zinn <small>Digitally signed by Caryn Zinn DN: c=CA, ou=University of Manitoba, ou=Faculty of Kinesiology, email=zinn@umanitoba.ca, cn=Caryn Zinn</small> <hr/> ADR or Dean	Leisha Strachan  <small>Digitally signed by Leisha Strachan DN: c=CA, ou=University of Manitoba, ou=Faculty of Kinesiology, email=leisha.strachan@umanitoba.ca, cn=Leisha Strachan</small> <hr/> Department Head <hr/> Chair, COVID-19 Research Recovery Team	Note: When the department head, and ADR or Dean have signed, the form should be submitted to crsc_research@umanitoba.ca by Friday at 4:30pm. Otherwise, the request will be reviewed by CRRT at the next meeting. Processing time may take 1-2 weeks from receipt of the completed form.
Approvals:  <small>Digitally signed by Dr Craig Forshaw DN: c=CA, ou=University of Manitoba, ou=Faculty of Kinesiology, email=forshaw@umanitoba.ca, cn=Dr Craig Forshaw</small> <hr/> Principal Investigator Caryn Zinn <small>Digitally signed by Caryn Zinn DN: c=CA, ou=University of Manitoba, ou=Faculty of Kinesiology, email=zinn@umanitoba.ca, cn=Caryn Zinn</small> <hr/> ADR or Dean	Leisha Strachan  <small>Digitally signed by Leisha Strachan DN: c=CA, ou=University of Manitoba, ou=Faculty of Kinesiology, email=leisha.strachan@umanitoba.ca, cn=Leisha Strachan</small> <hr/> Department Head <hr/> Chair, COVID-19 Research Recovery Team	Note: When the department head, and ADR or Dean have signed, the form should be submitted to crsc_research@umanitoba.ca by Friday at 4:30pm. Otherwise, the request will be reviewed by CRRT at the next meeting. Processing time may take 1-2 weeks from receipt of the completed form.								

APPENDIX D. RELIABILITY AND CROSS-SECTIONAL CONSENT FORM

Parent/Guardian Consent Form: Round 1 (Study 1-3)

- *Project title: **Sprinting Characteristics in youth female athletes across maturation***
- *Project Supervisor: **Dr. Craig Harrison***
- *Principal Researcher: **Richard Sylvester***

- I have read and understood the information provided about this research project in the Information Sheet. Yes No _____
- I understand that the results of which will be used for academic publications and conference presentations. All participants will remain de-identified throughout the course of the study to protect their privacy. All contact details will be kept strictly confidential. Do you consent to this: Yes No
- I understand that notes will be taken during the growth and maturation assessments (body height, mass etc): Yes No
- I understand that taking part in this study is voluntary (my child's choice) and that she may withdraw herself or I may withdraw my child and/or myself from the study at any time without being disadvantaged in any way: Yes No
- I understand if I withdraw my child/children and/or myself from the study, I will be offered the choice between having my child's or my identifiable data removed or allowing it to continue to be used. However, once the findings have been produced, removal of our data may not be possible: Yes No
- I agree to my child/children taking part in this research: Yes No
- I understand that my child can refuse to give assent to take part in this research: Yes No
- I wish to receive a summary of the research findings (please tick one): Yes No
- I wish to receive a summary of my individual research findings (please tick one): Yes No
- I understand that if my daughter is not sure or is worried about the assessment at any time, she and I can come and talk to the principal researcher, Richard Sylvester, and have those concerns met Yes No
- I understand that the time commitment will be approximately 1.5 hours on 4 different days spaced approximately 7 days apart. Yes No
- I acknowledge my daughter has not experienced a major injury in the past 3 months. Yes No
- I consent to my height being used to calculate maturation for my child Yes No

Height of biological mother..... Height of biological father.....

(Not knowing height of biological parents does not prevent study participation)

Child/children's name/s:

Parent/Guardian's signature: Date:

Parent/Guardian's name:

Parent/Guardian's Email (to send testing report):

Parents phone number (if appropriate).....

Participant date of birth (day/month/year):

Sport the participant plays that involves running or landing from a jump:

Approved by the Auckland University of Technology Ethics Committee on _____ AUTEK Reference number _____.

Note: The Participant should retain a copy of this form.

Participant code:

page 1 of 1

APPENDIX E. INTERVENTION CONSENT FORM

Parent/Guardian Consent Form: Round 2 (Study 4)

- Project title: *Sprinting Characteristics in youth female athletes across maturation*
- Project Supervisor: *Dr. Craig Harrison*, Principal Researcher: *Richard Sylvester*

- I have read and understood the information provided about this research project in the Information Sheet. Yes No
- I understand that the results of which will be used for academic publications and conference presentations. All participants will remain de-identified throughout the course of the study to protect their privacy. All contact details will be kept strictly confidential. Do you consent to this: Yes No
- I understand that notes will be taken during the growth and maturation assessments (body height, mass etc): Yes No
- I understand that taking part in this study is voluntary (my child's choice) and that she may withdraw herself or I may withdraw my child/children and/or myself from the study at any time without being disadvantaged in any way: Yes No
- I understand that if I withdraw my child/children and/or myself from the study then I will be offered the choice between having any data that is identifiable as belonging to my child/children and/or myself removed or allowing it to continue to be used. However, once the findings have been produced, removal of our data may not be possible: Yes No
- I agree to my child/children taking part in this research: Yes No
- I understand that my child can refuse to give assent to take part in this research: Yes No
- I wish to receive a summary of the research findings (please tick one): Yes No
- I wish to receive a summary of my individual research findings (please tick one): Yes No
- I understand that if my daughter is not sure or is worried about the assessment at any time, she and I can come and talk to the principal researcher, Richard Sylvester, and have those concerns met Yes No
- I understand that the time commitment is 30-35 minutes per session, two times per week for 8 weeks. There are also 2 days the week before and one day during week 4 and one day the week after (1.5 hours each) where assessments will occur: Yes No
- I understand that allocation to the respective training groups is done randomly, and my daughter may be in the sprint or jumping or group that does not sprint or jump: Yes No
- I understand that there is always small risk when participating in a sporting type activity. However, the risk will not be greater than that experienced during normal sport participation. Yes No
- I acknowledge my daughter has not experienced a major injury in the past 3 months. Yes No
- I consent to my height being used to calculate maturation for my child Yes No

Height of biological mother..... Height of biological father.....

(Not knowing height of biological parents does not prevent study participation)

Child/children's name/s:

Parent/Guardian's signature: Date :

Parent/Guardian's name:

Parent/Guardian's Email (to send testing report):

Parents phone number (if appropriate).....

Participant date of birth:

Sport the participant plays that involves running or landing from a jump:

Approved by the Auckland University of Technology Ethics Committee on AUTEK Reference number

Participant Code

page 1 of 1

This version was last edited in April 2018

APPENDIX F. RELIABILITY AND CROSS-SECTIONAL ASSENT FORM-
AGES 7-11



Participant Assent form (age 7-11): Part 1 of research project (study 1-3)

Researcher name: Richard Sylvester

TITLE OF RESEARCH

**SPRINTING CHARACTERISTICS IN
YOUTH FEMALE ATHLETES ACROSS
MATURATION**

(parent/caregivers please read to children)

This form will be kept for a period of 6 years

Reading the information sheet is very important. Did you read it and understand it?

YES NO

I will have to share the results of my project to my school, my teacher, other teachers and other students. I will not tell anybody it's you, so your name will be a secret. Can I use this information? - circle yes or no

YES NO

You can stop being part of this project whenever you want, and it is perfectly ok for you to do this. It is your choice. Do you understand? - circle yes or no

YES NO

If you stop being a part of the project, you can choose if I share your results with my teachers, other teachers and my school. Do you agree to let me share this information?

YES NO

Do you want to know your results?

YES NO

If you are not sure, or worried at any time during the project, you and your parent/guardian can come talk to me. Do you understand? - circle yes or no

YES NO

I may write notes during the research project. Please let me know how you feel about this by circling one of the words below.

Good
Fine
Not Sure
Worried

I have read the participant information sheet that says the activities we will do in this project.

YES NO

Do you agree to help with this project? -
Circle yes or no

YES NO

This is my photo



I hope we can do this together. It will be great to meet you. You will know who I am because of my photograph. I will also wear a badge with my name on, Richard, when I am at the Athlete Factory NZ.

Thank you for completing this form – please sign here if you feel that you understand what the project is about and give this form back to me please.

(Your signature)

(Date)


WHAT DO I DO IF I HAVE CONCERNS ABOUT THIS RESEARCH?

Any concerns regarding the nature of this project should be notified in the first instance to the Primary researcher, *Richard Sylvester*, rsylvester34@hotmail.com, 021922181.

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEK, Kate O'Connor, ethics@aut.ac.nz, 921 9999 ext 6038.

Approved by the Auckland University of Technology Ethics Committee on *type the date final ethics approval was granted*, AUTEK Reference number *type the reference number*.

APPENDIX G. RELIABILITY AND CROSS-SECTIONAL ASSENT
FORM- AGES 12-15



Assent Form: Round 1 (Study 1-3), age 12-15

- *Project title: Sprinting Characteristics in youth female athletes across maturation*
- *Project Supervisor: Dr. Craig Harrison*
- *Principal Researcher: Richard Sylvester*

I have read and understood the sheet telling me what will happen in this study and why it is important.

I understand that notes will be taken during the study: Yes No

I understand that taking part in this study is voluntary (my choice) and that I may choose to stop at any time without getting in trouble: Yes No

If I stop being part of the study, I understand that I will be offered the choice between having any information that that other people can know is about me removed or letting the researcher keep using it. I also understand that sometimes, if the results of the research have been written, some information about me may not be able to be removed.: Yes No

I agree to take part in this research: Yes No

I want to know the results of the research findings (please tick one): Yes No

I want to know my individual results (please tick one): Yes No

I understand that if I am worried about the assessment at any time, I can come and talk to the principal researcher, Richard Sylvester, and have those concerns met

I understand that the time commitment will be approximately 1.5 hours on 4 different days spaced approximately 7 days apart.

Participant's signature:

Participant's name:

Parent/Guardian's signature:

Parent/Guardian's name:

Parent/Guardian's Contact Details (if appropriate):
.....
.....
.....
.....

Date: _____

Approved by the Auckland University of Technology Ethics Committee on _____ AUTEK Reference number _____

Note: The Participant should retain a copy of this form.

APPENDIX H: INTERVENTION ASSENT FORM- AGES 7-11



Participant Assent form (age 7-11): Part 2 of research project (Study 4)

Researcher name: Richard Sylvester

TITLE OF RESEARCH

**SPRINTING CHARACTERISTICS IN
YOUTH FEMALE ATHLETES ACROSS
MATURATION**

(parent/caregivers please read to children)

This form will be kept for a period of 6 years

Reading the information sheet is very important. Did you read it and understand it?

YES NO

I will have to share the results of my project to my school, my teacher, other teachers and other students. I will not tell anybody it's you, so your name will be a secret. Can I can use this information?- circle yes or no

YES NO

You can stop being part of this project whenever you want and it is perfectly ok for you to do this. It is your choice. Do you understand?- circle yes or no

YES NO

If you stop being a part of the project, you can choose if I share your results with my teachers, other teachers and my school. Do you agree to let me share this information?

YES NO

Do you want to know your results?

YES NO

If you are not sure, or worried at any time during the project, you and your parent/guardian can come talk to me. Do you understand? - circle yes or no

YES NO

With the 3 groups, one will only sprint, the other only jump and the last one will only test. The group that only tests is just as important as the other groups. Do you understand that you could be in one of those groups?- circle yes or no

YES NO

I may write notes during the project. Please let me know how you feel about this by circling in one of the words below.

Good
Fine
Not Sure
Worried

If you agree to help with the project, I will need your help for 30-50 minutes, two times per week for 8 weeks. There are also 2 days the week before and one day after (1.5 hours each) where I need your help. Do you understand?- circle yes or no

YES NO

Do you agree to help with this project? - Circle yes or no

YES NO

This is my photo



I hope we can do this together. It will be great to meet you. You will know who I am because of my photograph. I will also wear a badge with my name on, Richard, when I am at the Athlete Factory NZ.

Thank you for completing this form – please sign here if you feel that you understand what the project is about and give this form back to me please.

----- (Your signature)

----- (Date)

WHAT DO I DO IF I HAVE CONCERNS ABOUT THIS RESEARCH?

Any concerns regarding the nature of this project should be notified in the first instance to the Primary researcher, *Richard Sylvester*, *rsylvester34@hotmail.com*, 021922181.

Concerns regarding the conduct of the research should be notified to the Executive Secretary, AUTEK, Kate O'Connor, *ethics@aut.ac.nz*, 921 9999 ext 6038.

Approved by the Auckland University of Technology Ethics Committee on type the date final ethics approval was granted, AUTEK Reference number type the reference number.

APPENDIX I. INTERVENTION ASSENT FORM- AGES 12-15



AUT

TE WĪHANGA ARONUI
O TĀMAKI MĀKAU RAU

Assent Form: Round 2 (Study 4), age 12-15

- → Project title: *Sprinting Characteristics in youth female athletes across maturation*
- → Project Supervisor: *Dr. Craig Harrison*
- → Principal Researcher: *Richard Sylvester*

- I have read and understood the sheet telling me what will happen in this study and why it is important.
- I understand that notes will be taken during the study: Yes No
- I understand that taking part in this study is voluntary (my choice) and that I may choose to stop at any time without getting in trouble: Yes No
- If I stop being part of the study, I understand that I will be offered the choice between having any information that other people can know is about me removed or letting the researcher keep using it. I also understand that sometimes, if the results of the research have been written, some information about me may not be able to be removed.: Yes No
- I agree to take part in this research: Yes No
- I want to know the results of the research findings (please tick one): Yes No
- I want to know my individual results (please tick one): Yes No
- I understand that if I am worried about the assessment at any time, I can come and talk to the principal researcher, Richard Sylvester, and have those concerns met
- I understand that the time commitment is 30-50 minutes per session, two times per week for 8 weeks. There are also 2 days the week before, one day during week 4 and one day the week after (1.5 hours each) where assessments will occur: Yes No
- I understand that allocation to the respective training groups is done randomly and I may be in the sprint or jumping or group that does not sprint or jump: Yes No
- I understand that there is always small risk when participating in a sporting type activity. However, the risk will not be greater than that experienced during normal sport participation.: Yes No

Participant's signature: → _____

Participant's name: → _____

Parent/Guardian's signature: → _____

Parent/Guardian's name: → _____

Parent/Guardian's Contact Details (if appropriate): _____

Date: → _____

Approved by the Auckland University of Technology Ethics Committee on _____ AUTEK Reference number: _____

Note: The Participant should retain a copy of this form.

page 1 of 1

This version was last edited on April 30 2018

The End