Assessment and manipulation of training practices in adolescent athletes

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Assessment and manipulation of training practices in adolescent athletes

In Total Fulfilment of the Degree of

Doctor of Philosophy

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Statement of Authorship and Sources

"This thesis contains no material that has been extracted in whole or in part from a thesis that I have submitted towards the award of any other degree or diploma in any other tertiary institution.

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All research procedures reported in the thesis received the approval of the relevant Ethics/Safety Committees (where required)."

Charles Dudley

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List of abbreviations

ACWR	Acute to chronic work to rest ratio
ASR	Anaerobic speed reserve
AU	Arbitrary units
bTRIMP	Banisters training impulse
CI	Confidence interval
CMJ	Countermovement jump
CV	Coefficient of Variation
DC	Davis cup
DMSP	Developmental model of sports participation
dRPE	Differential ratings of perceived exertion
ES	Effect size
eTRIMP	Edwards training impulse
F	Female
GAS	General Adaptation Syndrome
GNSS	Global Navigation Satellite Systems
HPT	High Plyometric training
HR	Heart rate
HRR	Hazard risk ration
HSR	High Speed Running
ICC	Intraclass correlation coefficient
iHSR	Individualised High Speed Running
IMTP	Isometric midthigh pull

iTRIMP	Individualised training impulse
LPT	Low plyometric training
LTAD	Long term athletic development
luTRIMP	Lucia's training impulse
M	Male
MAS	Maximal aerobic speed
N	Newtons
NASA-TLX	National Aeronautics and Space Administration Task-load Index
NRMSE	Normalised root mean square error
OR	Odds Ration
PHV	Peak height velocity
PRISMA	Preferred reporting items for systematic review and meta-analyses
PWV	Peak weight velocity
RFD	Rate of force development
RM	Repetition maximum
RR	Relative Risk
RS	Regional squad
S.D.	Standard deviation
S&C	Strength and conditioining
SRSS	Short recovery and stress scale
sRPE	Session ratings of perceived exertion
sRPEmus	Session ratings of perceived exertion - muscular
sRPEres	Session ratings of perceived exertion - respiratory
SSG	Small-sided games

SSS	Sports specific skills
TE	Typical error
TRIMP	Training impulse
vGRF	Vertical ground reaction force
vHSR	Very high speed running
VIF	Variance inflation factor
vLT	Velocity at lactate threshold
vOBLA	Velocity at onset of blood lactate accumulation
Yo-Yo IR1	Yo-Yo intermittent recovery level 1
YPDM	Youth physical development model

Abstract

Adolescent athletic development is a complex process. There are a number of challenges adolescent athletes face that influence their training practices. As such, this thesis aimed to 1) investigate the methods of monitoring and the distribution of training practices of adolescent athletes and examine the relationship with changes in physical qualities; and 2) assess how manipulating task-constraints (i.e., pitch size and player numbers) can influence the physical, technical and subjective task-load demands of training. To investigate these aims, 81 individuals were recruited across four study in conjunction with the industry partner, St Joseph's Nudgee College.

Study one systematically examined the research assessing internal and external methods of monitoring training load and changes in physical qualities, injury, or illness in adolescent athletes. The most reported load monitoring tools were session ratings of perceived exertion (n = 29) and training duration (n = 22). Results of the best-evidence synthesis identified moderate evidence of positive relationships between resistance training volume load and improvement in strength, and between throw count (i.e., number of pitches or bowls) and injury. However, evidence for other relationships between training load and change in physical qualities, injury, or illness were limited or inconsistent.

Study two quantified the training loads in adolescent rugby players, as well as the relationship between training loads and changes in physical qualities, and the changes in levels of stress and recovery throughout an 8-week pre-season period. Subjects completed (mean ± S.D) 5.60 ± 1.60 total training sessions per week, with 2.45 ± 0.34 resistance training sessions and 2.73 ± 0.54 field training sessions. Conditioning drills had the greatest running intensity (145.2 ± 47.8 m/min), whereas small-sided games (SSG) had the greatest acceleration density (0.46 ± 0.13 AU/min). Significant improvements ($p < 0.05$) in isometric mid-thigh pull (IMTP) peak force, Bench Press, and 2km run time were observed. Large degrees of multi-collinearity were present (all variance inflation factor > 10). Relationships between training load variables and changes in physical qualities were assessed using elastic net regression, with number of full body exercises having the greatest importance.

As identified in study two, the IMTP is a commonly implemented method of assessing strength. Study three investigated the validity and reliability of strapped and taped grip, figure eight straps, and bare hand grip during the IMTP. Compared to the straps and tape condition, using only bare hands to grasp the bar reduced peak force ($p < 0.01$) while the figure eight strap condition allowed for similar ($p = 0.42$; ES = 0.08 ± 1.14) outcomes. All conditions were found to have acceptable reliability (CV% = 5.36 - 5.67%) for peak force, but all rate of force development (RFD) and impulse outcome measures were not reliable irrespective of grip. These findings demonstrate that practitioners who wish to use the IMTP to assess peak force should use either straps and tape, or figure eight straps. It is advised that practitioners use figure eight straps, as was used in study two, due to their equivalence in reliability, but increased efficiency and practicality.

Study four assessed the variability of physical, technical, and subjective task-load demands in SSG, and the effect of manipulating of pitch size and player numbers in SSG on these demands in adolescent Rugby Union players. This study was conducted as SSG were the most commonly used conditioning tool evidenced in study two. In each condition subjects played 4 × 3-min periods of an SSG. Games were completed with either 4 × 4, 6 × 6 or 12 × 12 players on either a small (W: 25 m, L: 30 m), medium (W: 30 m, L: 40 m), or large (W: 35 m, L: 50 m) sized pitch. A substantial range of variability was observed in technical (CV = 25.00 to 52.38%), physical (CV = 4.12 to 51.18%) and subjective task-loads (CV = 7.65 to 17.14%) between identical games. Reducing player numbers increased physical demands such as m/min (ES range = 0.44 to 1.45; p = <0.01), technical exposures such as total involvements (ES range = 0.04 to 0.63; p range = <0.01 to 0.64) and effort, physical and temporal task-loads. Increasing pitch size caused greater movement demands such as m/min (ES range = 0.11 to 0.79; p = <0.01 to 0.62), but did not change the technical demands.

Chapter 1. Introduction

Organised sport is a popular leisure activity across the world, with numerous benefits for participants, including improvements in physical, psychological, and social health and wellbeing [6]. Sport includes activities that involve physical exertion and skill, has elements of competition and rules, and is governed through formal organisations [7]. Whilst sport offers numerous health and wellbeing benefits, for a select few athletes, the motivation to participate in sport lies with achievement and status, with a desire to progress from recreational physical activity to achieving selection at higher levels [8]. Given the popularity of organised sport, significant research has been devoted to establishing best-practice training models.

One population group with high levels of participation in organised sports is adolescents [6]. Adolescence begins at the onset of puberty, and is broadly defined as being between the ages of 10 – 19 years of age [9, 10]. This period represents the transition between childhood and adulthood. Through puberty there are significant changes that occur in both males and females, primarily caused by the production of sex hormones, such as testosterone increasing muscle mass [1, 2]. These changes are both cognitive (e.g., information processing) and physical (e.g., height and muscle mass) [1, 2]. Some of the changes that occur throughout maturation are transient and characterised by reductions in motor skills, and consequently increased injury risk [13]. Given the changes that occur throughout adolescence, ensuring appropriate training for sports will have long term benefits, for both athleticism and general well-being [14].

To achieve mastery in a domain, adolescent athletes must adopt intensive practice. Intensive practice was first characterised by the '10,000 Hour' rule which indicates that mastery of a skill can be achieved through 10,000 hours of deliberate practice (i.e., practice that is purposeful) [15]. However, this rule has attracted criticism for being too simplistic, and failing to account for the broad range of practice activities and athletic competencies that must be trained to achieve mastery in many sports [16]. Nonetheless, the principle that a large amount of training is required for elite performance often remains true. Athletes at higher levels of sport are regularly fitter, faster, stronger, and more technically competent than their counterparts at lower levels of sport [17]. In order to facilitate better physical qualities, athletes require exposure to a range of training modalities, at progressively greater intensities, in addition to sport specific training, to promote adaptation.

One model that demonstrates how athletes adapt to training is the General Adaptation Syndrome (GAS). The GAS is a model that demonstrates the interaction between stress, and potential adaptation and maladaptation [18]. In relation to exercise, the GAS operates on the assumption that exercise is a stressor, and it causes disruption to allostasis [18]. The premise of the GAS model is that following stress, such as exercise, adaptation to the stress will occur if adequate recovery is allowed. However, in the absence of adequate recovery, a state of "exhaustion" will occur, characterised by an acute reduction in performance [18]. However, the GAS model has been criticised for being an oversimplification of the training process, and ignoring other drivers of adaptation [19]. The ability to adequately recover and adapt to training load is affected by a multitude of factors such as nutrition [20], sleep [21], and physical qualities [22].Further, adolescent athletes have a number of additional key challenges that influence their training schedules, and therefore the load experienced.

Adolescent athletes often play multiple sports, across multiple teams, while also managing academic commitments, adding to the complexity of long-term athletic development. These complexities have been illustrated by Scantlebury et al. [5] (Figure 1.1) and comprises of four key challenges. The first challenge is a scheduling tug of war, whereby many different stakeholders, for example multiple sports or teams, have misaligned aims [23]. The second challenge is that of organised chaos, with adolescent athletes often having highly variable training loads as a result of a convoluted schedule [24]. Training must comprise of a balance of both resistance and field activities to ensure both sports specific skills and physical qualities are developed. The third challenge is the mismatch between the coach and athletes, with the prescribed load by coaches often not aligning to the athletes internal response to the load [25]. The fourth challenge is that of the student-athlete, whereby a balance between academic and sporting pursuits must be found [26]. These challenges influence the training for adolescent athlete and highlight the need to conduct research into the demands placed on adolescent athletes.

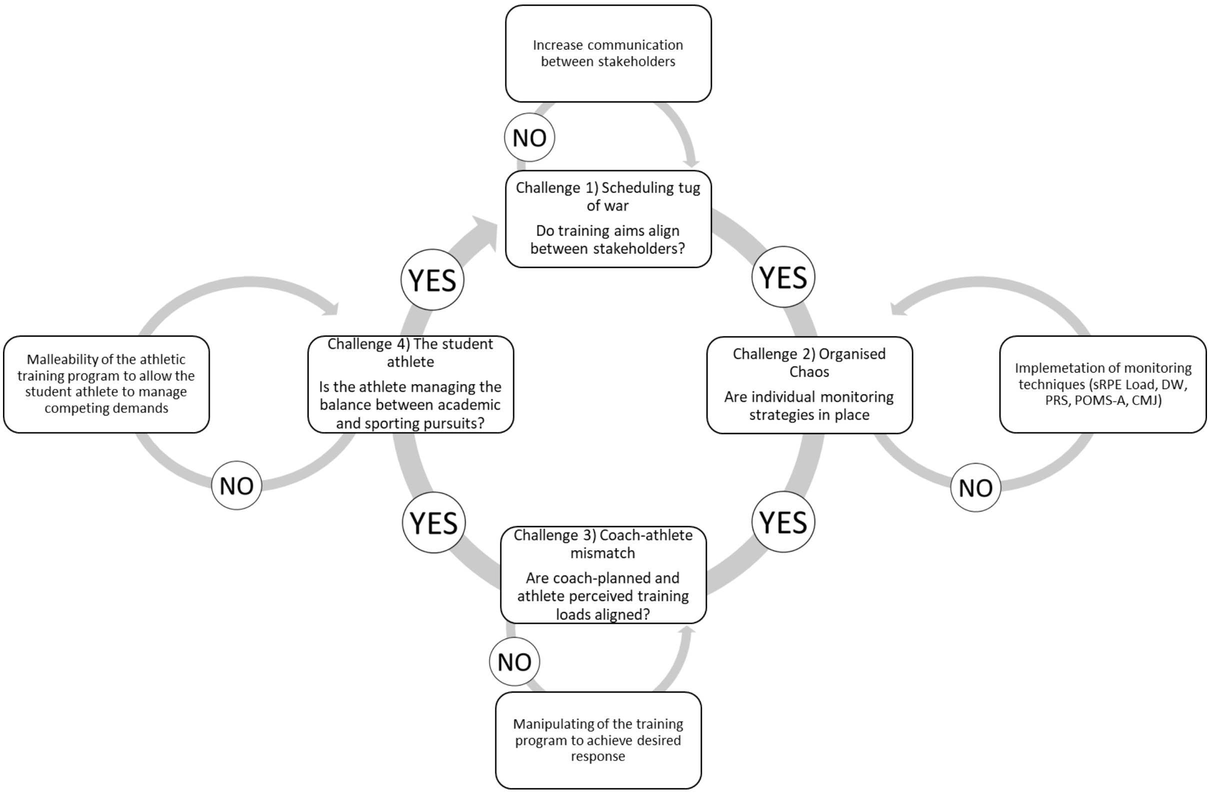


Figure 1.3. An overview of the challenges and solutions facing adolescent athletes [5, 27].

Training load is a commonly used construct to quantify the demands placed on athletes. Broadly, load is defined as the intensity (e.g., external load) of the work performed, multiplied by the volume (e.g., number of repetitions) of the bout of physical activity [28]. External methods of monitoring load measure the work performed by an athlete, including resistance training volume load (sets × reps × load) and running metrics through global navigation satellite systems (GNSS) [29]. Alternatively, internal load monitoring methods capture the physiological (e.g., heart rate; HR) and psychophysiological (e.g., session rating of perceived exertion; sRPE) responses to the external load [29]. To accurately assess the load-response relationship, it is important to understand what tools are commonly used to monitor training load. However, there are many different methods of measuring the intensity and volume of physical activity such as global navigation satellite systems (GNSS), heart rate (HR) telemetry, resistance training volume load (sets × repetitions × weight (kg)), and session ratings of perceived exertion (sRPE). The variety of training load assessment tools make the uniform quantification of training load difficult, particularly across different training modalities. Additionally, there are practical considerations for coaches, with some measurement tools being expensive, and requiring expertise to operate and analyse the data [30]. Given the range of methods of monitoring training load, it is imperative to understand how training load can be monitored with special populations such as adolescents.

Previous research has investigated the resistance and field-based training loads of adolescent athletes [31, 32]. For example, Weakley et al. [31] investigated the resistance training loads of adolescent rugby players and its relationship to changes in strength, speed, sprint momentum, and jump characteristics [31]. It was found that resistance training volume load was related to increases in strength, indicating that the monitoring of resistance training volume load may be a key monitoring tool, given the importance of strength development. Additionally, Phibbs et al., [32] investigated field-based training volume of adolescent athletes, with the primary finding being that training load was highly variable between athletes as a result of competing in school, club and representative commitments. However, to date there has not been a systematic review of the literature in relation to the load-response relationship in adolescent athletes. Further, there is very little research that provides descriptive observations of both the field and resistance training demands placed upon adolescent athletes. Therefore a systematic review is warranted to synthesise the available research in relation to the training load measures used, and their relationship to changes in physical qualities, in adolescent athletes.

Adolescent athletes are recommended to complete 2-3 resistance training sessions per week in order to develop physical qualities, such as strength [33]. Strength is an important physical quality as it is related to sporting actions, such as acceleration, jumping and change of direction, as well as reducing the risk of injury and underpinning other physical qualities, such as power [34-36]. Stronger athletes are also more likely to progress to higher levels of sport [17]. Strength is often assessed through dynamic repetition maximum testing (e.g., one repetition maximum (1RM)), however this can be time consuming. Further, 1RM testing may be inappropriate in athletes with low training ages and poor movement competency. Therefore, other methods of assessing maximal strength may be appropriate.

One common alternative method of assessing maximal strength is the isometric midthigh pull (IMTP) [37]. The IMTP is performed by athletes pulling on an immovable bar, in a similar position to the second pull of the clean [37]. This exercise is low skill and safe, however, a variety of different methods of performing the IMTP are reported in the literature, such as grasping the bar with a variety of grips including overhand, underhand and mixed grip and the use of either straps, straps and tape, or bare hands [34, 38]. Securing athletes to the bar using straps and tape is the "gold standard" method, as it is assumed to negate grip strength as a limiting factor [37]. However, the use of straps and tape is time consuming. Further, the validity and reliability of these different methods have not previously been investigated. Ensuring testing methods are valid and reliable enables coaches to accurately monitor changes in change in physical qualities.

In addition to more developed physical qualities, better athletes are commonly more tactically and technically proficient in their sport compared to their counterparts [17]. Increasingly it is being understood that the tactical, technical, physical, and psychological elements of sport (termed the four "co-actives" [39]) are intrinsically linked and should rarely be trained in isolation [40]. Therefore, strategies to simultaneously target multiple co-actives of sport, such as SSG, are becoming more common [41]. The growing popularity of SSG is partly as a result of the increased attention being paid to a model of training periodisation called "Tactical Periodization" [40], which emphasises integration of the four co-actives. This training methodology is thought by some coaches to be more effective than traditional training whereby different co-actives of the sport would be viewed as being separate from one another [40]. Coaches using this model will utilise constraints-based theory, whereby drill constraints are manipulates the drill constraints, such as changing the number of players in a drill, to shift the emphasis of their training, as opposed to attempting to train different co-actives in isolation. Given the popularity of this training methodology within sport, understanding the effect of manipulating different constraints will assist coaches in targeted training prescription.

Understanding how to manipulate training drills enables coaches to align training prescription to the desired outcomes. Every drill has a set of environmental (e.g., pitch size), individual (e.g., fitness level), or task (e.g., rules) constraints that can be manipulated to influence the physical, tactical and technical demands of the drill [42]. Coaches may manipulate drills to emphasise certain physical qualities or increase or reduce the overall demands placed on the athlete. Scantlebury et al, [5] proposed that altering the demands placed on student athletes can help to ensure that training demands are appropriate to manage competing demands, such as other sports or academic requirements. For example, coaches may reduce training demands when external training (i.e., representative or club training) is increased, by manipulating task environmental constraints, such as reduced field size. This can help ensure a balanced approach to athletic development, and reducing the risk of negative outcomes, such as overuse injuries or burnout. Given this, it is important for coaches to understand how to manipulate drills in order to alter training demands and to ensure appropriate application of load for the athletes.

Coaches will often manipulate the environmental constraints of drills to achieve a desired training outcome [42]. It has been shown that through the manipulation of constraints such as pitch size and player numbers, the running demands of a drill can significantly change [42]. Further, drill manipulation can alter the tactical or technical emphasis, such as reducing player numbers to increase technical exposures [42]. Despite this, there remains a paucity of research on the effect of simple drill manipulation on tactical, technical and physical demands in both adolescent and adult athletes [42, 43]. Developing a greater understanding of how to manipulate drills will facilitate coaches in designing training drills that can accurately emphasise different elements of the four co-actives to inform long-term athletic development models that provide greater detail on appropriate manipulation of sports training.

There are currently gaps in the literature pertaining to the training of adolescent athletes. In particular, there is little information as to the field and resistance-based training practices of adolescent athletes, particularly in Australian schools. Therefore, the first aim of this thesis is to add to the current knowledge in the training of adolescent athletes by:

1 Evaluating the training practices, both resistance and field-based training, of adolescent athletes, and the changes in physical characteristics, stress and recovery.
    a. Systematically examine the current literature reporting the training load monitoring methods used in adolescent athletes.
    b. Systematically examine the current literature reporting the relationship between training load and change in physical qualities in adolescent athletes.

   c. Report the distribution of training loads, both field and resistance training, in adolescent rugby players.
   d. Investigate the relationship between training loads and changes in physical qualities in adolescent rugby players.
   e. Investigate the relationship between training loads and changes in subjective levels of stress and recovery.

To increase the practicality of the assessments, the methodology used in study one to assess the changes in physical qualities did not follow standard methodological guidelines. Therefore, the second aim of the thesis was to:

2 Validate the methodology used to assess the changes in physical qualities, in the studies that investigated into the Aim 1.
   a. Assess the inter-day reliability and validity of different grips in the isometric midthigh pull (IMTP)

The findings from investigating aim 1 showed that SSG are a common method of physical conditioning. As such the final aim of this thesis was to:

3 Evaluate the effect of manipulating environmental constraints on the physical, technical and tactical demands in SSG.
   a. Investigate the effect of pitch size manipulation on technical, tactical, and physical demands in SSG in adolescent Rugby Union.
   b. Investigate the effect of player number manipulation on technical, tactical, and physical demands in SSG in adolescent Rugby Union.

Chapter 2. Literature Review

This literature review is a non–exhaustive overview of models of youth athletic development, load monitoring, and small sided games. Given that Chapter 4 is a systematic review and best evidence synthesis in the topic of load monitoring, discussion of load monitoring will be brief.

2.1 Overview of youth athletic development

Youth athletes represent a special population group within the field of athletic performance and are distinctly different from their adult counterparts due to the physiological changes that occur throughout maturation, and other factors such as limited training history. The importance of not treating adolescent athletes like miniature adults has previously been documented [5], therefore, specific training models have been developed to ensure appropriate exercise prescription [2, 44]. Developing a method of physical training for adolescent athletes is not a new phenomenon, with evidence of some structured physical training of adolescents from before 400 BC [45]. Multiple modern models to help guide the development of long-term athletic development have since been proposed, such as the development model of sports participation (DMSP) [46], long term athletic development (LTAD) model [1], and the youth physical development model (YPDM) [2]. These models provide a comprehensive understanding of the various aspects of adolescent athletic development.

2.1.1 Developmental model of sports participation

The DMSP was initially conceived in 1999, in a paper that explored the role of family in the development of elite athletes (Figure 2.1) [46]. This model presents seven postulates for youth athletic development. Five of these postulates focus on the effect of sampling and deliberate play on personal development, participation and performance, whilst two focus on the transition from childhood to adolescence and from early to late adolescence. Three phases of sport-specific development were identified, being the sampling phase (6 – 12 years old), the specialising phase (13 – 15 years old) and the investment phase (older than 16). The DMSP proposes exposure to a variety of sports in the sampling stage does not hinder performance and increases longevity in both performance and participation within sports. The model also advocates for high amounts of deliberate play throughout early adolescence as a means to building intrinsic motivation and improving motor skills. Following early adolescence, the DMSP proposes that children may either begin to specialise in their chosen sport at increasingly higher levels, or sample multiple sports recreationally. Whilst the DMSP provides a simple framework for sampling (i.e., exposure to a diverse range of sports), deliberate play (i.e., purposeful practice) and specialisation in adolescent athletes, there are varying levels of evidence supporting its implementation [47]. Further, the DMSP does not describe the type of activity that should be undertaken, ignoring training that may build physical capacities, such as resistance training.

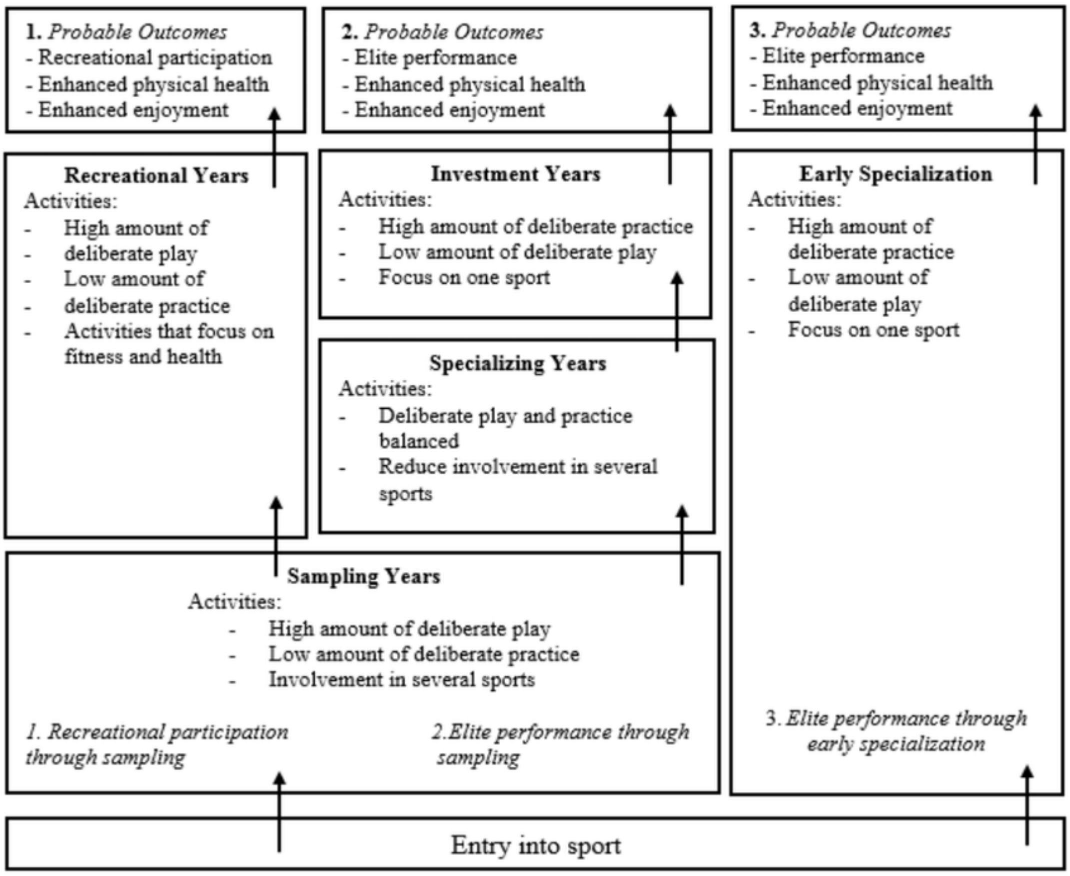


Figure 2.1. The developmental model of sports participation.(pp. 79)_[3]

2.1.2 Long term athletic development model

Following the work of Côté in establishing the DMSP, Balyi and Hamilton proposed an updated model, the LTAD model (Figure 2.2) [1]. The LTAD Model separates the training of athletes into early and late specialisation sports, where early specialisation refers to sports such as gymnastics, where athletes reach their competitive peaks earlier than late specialisation sports such as team sports [1]. There are a number of differences between the LTAD model and the DMSP, such as different terminology and descriptions of the stages of development, different methods of assessing “age”, and the introduction of the concept of windows of trainability [1]. Whilst the theoretical basis for some of these concepts has been challenged [2], the LTAD model represents a significant advancement in the understanding of training youth athletes, primarily due to the acknowledgement that there should be a logical, phased approach to the introduction of different training concepts, and that athletes may mature at different rates, and therefore have different requirements [1].

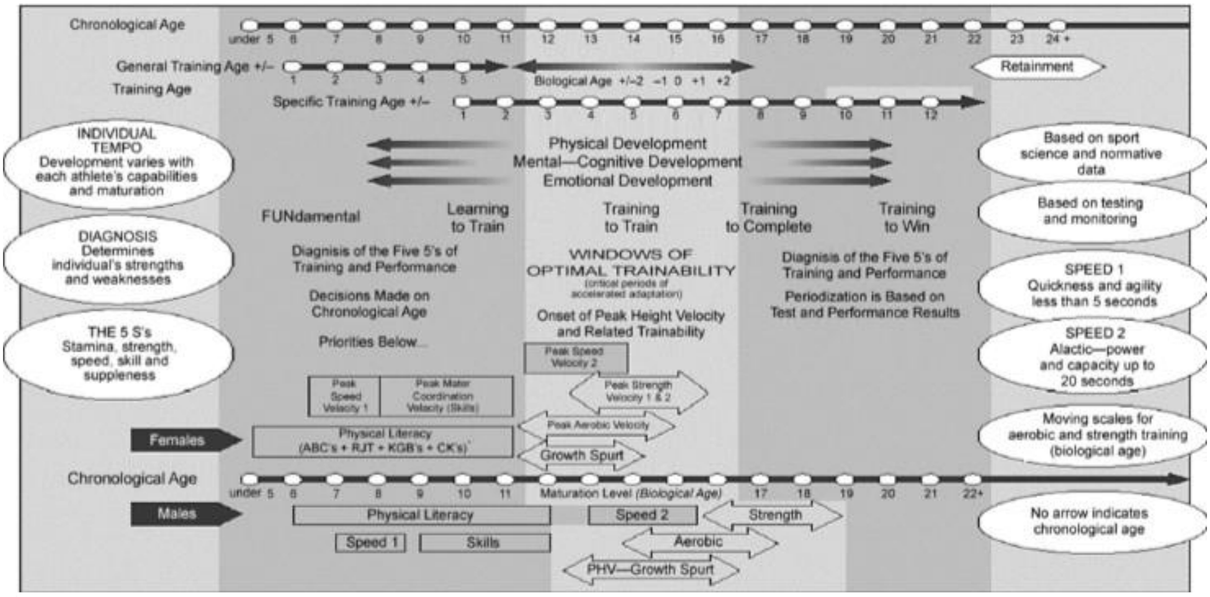
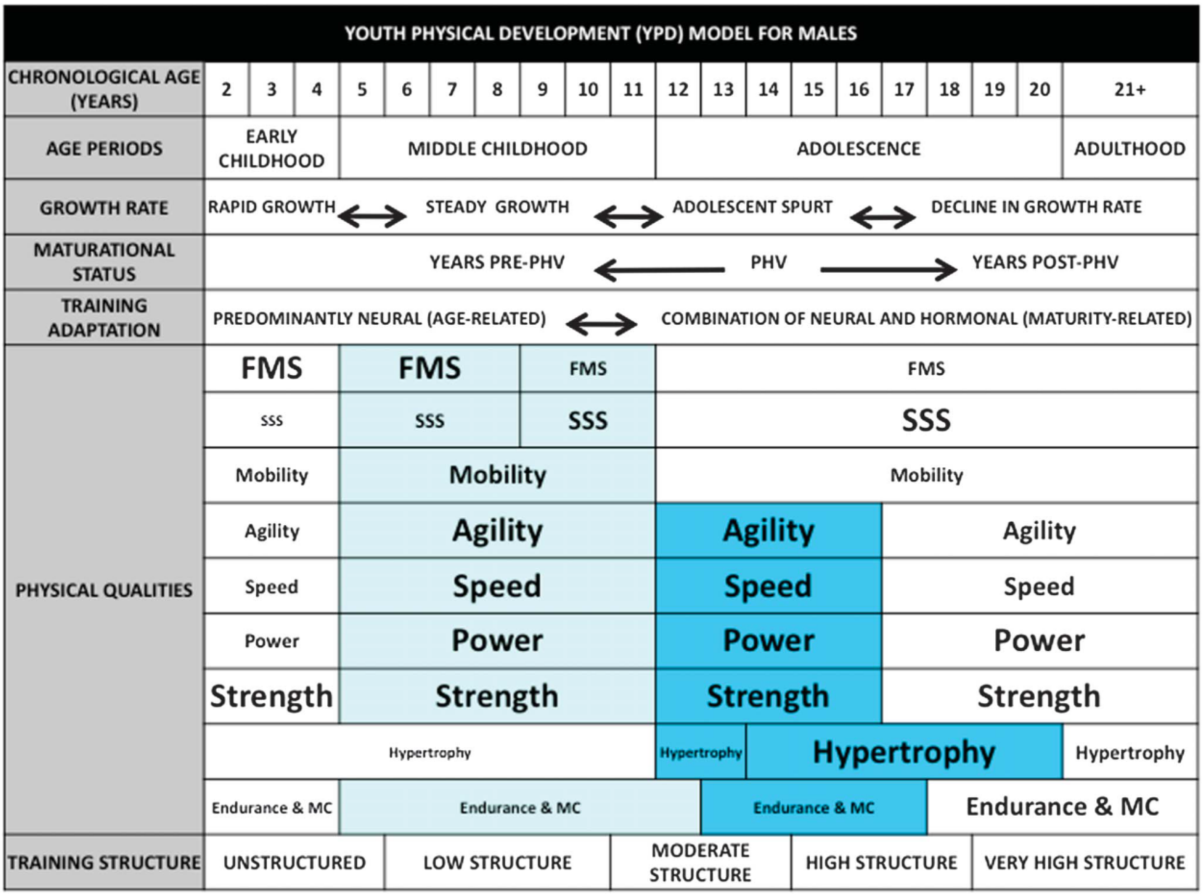


Figure 2.2 The long term athletic development model (pp. 12) [1]

2.1.3 Youth physical development model

The most recent adolescent development model is the YPDM [2]. Some key features of the YPDM were the introduction of gender specific guidelines due to differing rates of maturation, and a greater emphasis on biological landmarks of development such as PHV and peak weight velocity (PWV) [2]. Additionally, the YPDM illustrates that all physical qualities should be trained throughout the entire period of maturation, with the emphasis changing at different time points [2]. Further differentiating the YPDM from the LTAD model is the inclusion of sports specific skills as a physical quality that should be emphasised throughout adolescence [2]. Given the importance of emphasising different qualities, and thus different forms of training, it is important to be able to accurately assess the training load distribution of adolescent athletes, to ensure training is being conducted appropriately [2]. Additionally, understanding of the methods to assess physical qualities is important to be able to accurately evaluate strength and conditioning programs.



<table>
<tr><th colspan="21">YOUTH PHYSICAL DEVELOPMENT (YPD) MODEL FOR MALES</th></tr>
<tr><td>CHRONOLOGICAL AGE (YEARS)</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21+</td></tr>
<tr><td>AGE PERIODS</td><td colspan="3">EARLY CHILDHOOD</td><td colspan="7">MIDDLE CHILDHOOD</td><td colspan="9">ADOLESCENCE</td><td>ADULTHOOD</td></tr>
<tr><td>GROWTH RATE</td><td colspan="20">RAPID GROWTH ↔ STEADY GROWTH ↔ ADOLESCENT SPURT ↔ DECLINE IN GROWTH RATE</td></tr>
<tr><td>MATURATIONAL STATUS</td><td colspan="20">YEARS PRE-PHV ← PHV → YEARS POST-PHV</td></tr>
<tr><td>TRAINING ADAPTATION</td><td colspan="20">PREDOMINANTLY NEURAL (AGE-RELATED) ↔ COMBINATION OF NEURAL AND HORMONAL (MATURITY-RELATED)</td></tr>
<tr><td rowspan="9">PHYSICAL QUALITIES</td><td colspan="3">FMS</td><td colspan="4">FMS</td><td colspan="3">FMS</td><td colspan="10">FMS</td></tr>
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<tr><td>TRAINING STRUCTURE</td><td colspan="4">UNSTRUCTURED</td><td colspan="5">LOW STRUCTURE</td><td colspan="4">MODERATE STRUCTURE</td><td colspan="4">HIGH STRUCTURE</td><td colspan="3">VERY HIGH STRUCTURE</td></tr>
</table>

Figure 2.3. The youth physical development model for males (pp. 63) [2]

The DMSP, LTAD and YPDM models provide a comprehensive framework for adolescent athletic development, with each model providing different elements to optimise development. The DMSP's focus on personal development, participation and performance is then built on through the LTAD, which recognizes factors key to adolescent athletic development, such as maturation, and introduces the concept of windows of trainability. The YPDM serves as an extension of these previous models, including gender-specific guidelines, and emphasising the importance of training all physical qualities, particularly strength, throughout adolescence. A common theme throughout the majority of youth literature is the importance of strength development, with strength being related to factors such as reduced injury risk, and improved power [48, 49]. Further, the YPDM incorporates the development of sports-specific skills as being integral to development. Together, these three models can be used to assist practitioners in developing appropriate training protocols for adolescent athletes.

2.2 Load monitoring

Training monitoring is common in elite sport [50] and is becoming increasingly prevalent in adolescent sports due to increased access to, and investment in, technology [5]. The aim of load monitoring is to accurately determine the stress imposed by training on athletes. This is represented in Figure 2,4. whereby the external training load, combined with the individual characteristics of the athlete, cause an internal response, that subsequently facilitates a training outcome [4].

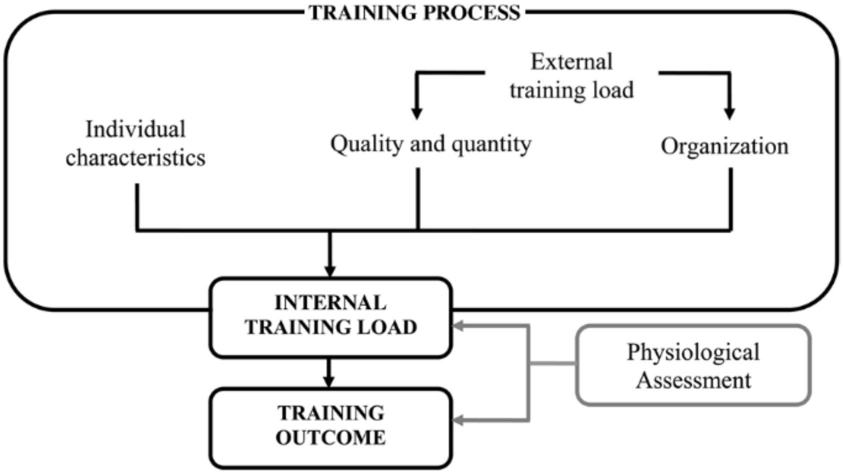

Figure 2.4. Description of the training process, retrieved from Impellizeri et al., (pp. 584) [4]

2.2.1 Resistance training load assessment

To develop key physical qualities such as strength and power, adolescent athletes will perform resistance training [31]. Historically, the appropriateness of resistance training in adolescent athletes has been a subject of conjecture, with it being considered potentially injurious [51]. However, this myth has been comprehensively debunked [2, 52] and it is recommended that adolescent athletes complete 2-3 resistance training sessions per week [33]. Whilst resistance training is recommended in adolescent athletes, it must be prescribed and progressed in an appropriate manner, and as such, resistance training loads should be monitored.

Commonly used external methods of monitoring resistance training load include the time spent resistance training, the repetition method, and the volume load method [53]. The repetition method involves counting the number of repetitions performed within a specific exercise (e.g., back squat), or body segment (e.g., lower body) over a micro-, meso-, or macrocycle [53]. However, the repetition method does not account for the load lifted, and is therefore limited in its ability to infer training stimulus [53]. The volume load method refers to the number of repetitions performed multiplied by the load the repetitions were performed with. The load used to calculate volume load may be either the absolute load (i.e., kilograms lifted), the relative load (i.e., percent one repetition maximum), or the relative load specific to the repetition maximum (i.e., percent of the repetition maximum for repetition range used) [53]. Volume load has been previously correlated to increases in strength [51]. As the volume load method accounts for both the volume, and intensity of resistance exercises, it may be more effective in inferring the training demands than the repetition method.

Resistance training load can also be monitored using internal methods such as session ratings of perceived exertion (sRPE) and set RPE (i.e., the RPE of each set) [53]. Common scales used include Borgs 15-category, Category Ratio-10, differential ratings of perceived exertion (dRPE), and OMNI-resistance exercise scales [53]. These scales require athletes to indicate the difficulty of a component of a training session, or the training session as a whole, on a scale, commonly between 1-10 (CR10) or 1-100 (CR100) [54]. Often these scales have verbal anchors to assist athletes (i.e., 5 = hard) [28]. Some scales will also require athletes to be more specific as to the nature, or body segment, which was exerted (e.g., breathlessness or muscular exertion) [54]. However, most subjective scales are limited in their ability to accurately assess the specific physiological or biological stress created by the training stimulus (e.g., hypertrophic or power stimulus). Subjective scales provide a good overview of the volume and intensity of training, however, should be used in conjunction with other load monitoring methods in order to ensure precise assessment of load.

Several studies have examined the resistance training load of adolescent athletes using both internal and external methods. However, there is high variability in the methods used, and sports reported. For example, academy aged football players reported an average of between 38 and 51 minutes of resistance training per week [55], in contrast to the 13 to 210 minutes reported in Rugby Union [31, 56]. Additionally, the weekly sRPE for resistance training is also highly varied with values between 196 and 1010 AU being reported [31, 57]. There is little research into the repetition volume, or volume load of adolescent athletes. Weakley et al., (2019) investigated the strength and conditioning practices in adolescent rugby players and found an average weekly volume load of 5443 kg (range = 932 to 11626). Given the relative dearth of information regarding the resistance training loads of adolescent athletes, further research is required.

2.2.2 Field training load assessment

To assess field-based training loads, several external load monitoring tools are commonly used, including training time, GNSS devices, and accelerometry [29, 56]. Whilst time spent training is a cheap and practical tool, it provides no information as to the intensity or type of training being performed, and therefore may have limited application in inferring a training stimulus. GNSS devices are commonly used in sports with high running demands, including Rugby Union [58]. Common metrics that can be derived from GNSS units include total distance, distances in different velocity bands, maximal velocity, and changes in velocity (i.e., acceleration and decelerations) [29]. These metrics can then be used to infer training load, and to assist in determining the specificity of training to the physical demands of match play [59].

Internal methods of monitoring field-based training load include sRPE and heart rate telemetry [28, 60]. Given the consistency between scales, a primary benefit of sRPE is it can be used to assess load across all training modalities, allowing for a global representation of training load. Further, different sRPE subscales are occasionally appropriate to assess the type of load, for example, breathlessness and muscular load [54]. Heart rate monitoring is another useful monitoring tool as athletes heart rate is directly correlated to oxygen uptake during continuous exercise [61], and therefore can be used to infer aerobic stimulus. Heart rates are generally reported as a percentage of maximal heart rate, or training impulse (TRIMP). There are several different versions of TRIMP, however, most use the time athletes spend in heart rate zones, multiplied by a weighting factor [62].

The field-based training loads of adolescent athletes have been examined using both internal and external methods, across multiple sports. Adolescent environments commonly have budgetary and staffing constraints, and as such, simple and cost-effective tools, such as sRPE, are often used. However, there is a large range of sRPE's reported for adolescent athletes both within and between sports. For example, weekly load in football has been reported to vary by as much as 300% between players [55], while adolescent Rugby Union players have reported weekly loads between 195 and 4888AU [31]. The highly variable loading of adolescent athletes is further emphasised by Phibbs et al., (2018) who found coefficients of variation of >10% across an in-season period.

With increased financial resources in adolescent sport, access to tools such as heart rate and GNSS devices are becoming more common. Heart rate variables have previously been explored in adolescent athletes in football [63-66] and Rugby Union [67]. Edwards TRIMP (eTRIMP) was commonly used, with weekly loads of 360 ± 104AU reported in academy Rugby Union players, and 217 ± 53AU reported in adolescent football [65, 67]. GNSS units are also becoming more common in adolescent environments, however, similar to other load monitoring methods, a large range in training loads has been reported [55, 56]. For example, total distances in adolescent Rugby Union athletes have been reported to have between subject CV of 30% and within subject CV of between 5 and 74% [56]. Given the variability of training loads reported in adolescent athletes, it is important to ensure individualised load monitoring programs.

2.2.3 Statistical controls and techniques for load monitoring

To assess the relationship between training loads and outcome variables, a variety of different statistical methodologies have been used. Throughout the literature, logistic and linear regression methodologies are common [68]. However, these methodologies are bound by stringent assumptions such as normality of residuals and homogeneity of variance, and multicollinearity [68, 69]. A measure of multicollinearity is variance inflation factor (VIF), with VIF scores greater than 10 indicating multicollinearity for the training variable [68]. It has previously been reported that training load variables share high degrees of multicollinearity, with training load data in adolescent rugby league players being reported as having inflation factors (VIF) between 3 and 224288, demonstrating high multicollinearity [68]. Therefore, more appropriate techniques such as dimension reduction, or feature selection algorithms may be more appropriate.

Dimension reduction techniques have been used in previous sporting literature [69]. A commonly used dimension reduction technique is principal component analysis. Principal component analysis can be used to take large, highly dimensional datasets and reduce them into variables called principal components. One study in youth football players used principal component analysis to examine the relationship between training loads prior to match day [70]. It was found that three principal components best represented training load, with the components characterised by either measures of volume, or measures of intensity. However, one of the limitations of principal component analysis, is that the newly constructed principal components, are often difficult to interpret, and then apply, which is key in a sporting context. Therefore, feature selection algorithms, while novel within a sporting context, may provide more context to training data.

Elastic net regression is a feature selection algorithm that may have applicability within sports. As opposed to dimension reduction techniques, feature selection algorithms can be used to identify the most important variables in a regression equation [71]. Therefore, the results can often be easier to interpret. Additionally, elastic net regression has also been demonstrated to have greater predictive accuracy than principal component and linear regression techniques in assessing the training load response in short track speed skaters [71]. Elastic net regression is a penalised linear regression model that uses a hybrid of the Ridge and Least Absolute Shrinkage and Selection Operator penalties [71]. The Ridge penalty shrinks coefficients of all variables towards zero, whilst the Lasso penalty shrinks some coefficients to zero. Due to the limitations of these penalties, a combination of the two will provide the best performance in the model [71]. Given the robustness of the elastic net regression, there is scope for further investigation into its use in sports.

2.2.4 Summary of load monitoring

This section has detailed the large number of methods of monitoring training load in adolescent athletes. Whilst numerous tools are available to practitioners, the selection of appropriate load monitoring tools will be dependent on various factors, including the budget and staffing experience of an organisation, and the sports being monitored. To assist practitioners in determining the load monitoring tool that may be appropriate in their environment a systematic review of current literature on the methods of monitoring internal and external training load, and their relationships with physical qualities, injury or illness, is warranted. Further, this section of the literature review has highlighted the large variation in training loads of adolescent athletes, even within the same environment. Therefore, practitioners and researchers should investigate the demands being placed on their athletes within their unique settings, to determine the appropriateness of training and subsequent interventions.

2.3 Small–sided games

SSG are a commonly used training method to simultaneously target tactical, technical, physical, and psychological development [42]. Although the popularity of SSG began in football, there has been rapid adoption in other sports, such as Rugby Union [40]. SSG are variations of a sport, whereby constraints have been manipulated, such as the alteration of pitch size, or player numbers. The use of SSG differs from traditional, closed, drills in that the sport in practiced in a manner that is more specific to the sport itself, therefore training skills in a more ecologically valid manner. Altering the environment of training through the manipulation of constraints, uses a pedagogical method called the "constraints led approach" [72]. Given SSG facilitate concurrent development of the four co-actives, they are a highly efficient method of training.

SSG are designed by altering the constraints of a task. Constraints are defined as 'the information, to shape or guide the (re)organisation of a complex adaptive system' [73]. Constraints can be manipulated to alter the tactical, technical, physical, or psychological outcome. A constraints led approach has been demonstrated to be more effective for skill acquisition than both differential learning, and prescriptive instruction [74]. Additionally, using a games-based approach to training has previously been shown to be as efficient as traditional training methods in developing aerobic fitness in sports including football, hockey, rugby and basketball [75-78]. Due to the efficacy of using SSG and constraint manipulation, they are commonly used for athletic development. Given their popularity, there is scope for research into improving the accuracy of SSG training prescription.

A common framework for constraint manipulation is Newell's model of constraints [72]. This model postulates that there are three categories of constraints, being the task, individual and environment [72]. Individual constraints include factors such as the athlete's maturation and level of skill or fitness. The environmental constraints refer to the broader context of the game, including aspects such as the physical environment (e.g., weather) and the social environment (e.g., crowd). Finally, task constraints refer to aspects such as the rules, pitch dimensions, and number of players. Given the task constraints are the easiest to acutely manipulate, they are the often the focus for coaches when SSG. Coaches will manipulate these constraints to alter the tactical, technical, physical, and psychological demands placed on athlete.

2.3.1 Task constraint manipulation

Manipulating task constraints will change the tactical and technical demands during SSG, by encouraging players to display certain behaviours, for example, passing more frequently. Different task constraints will influence the volume of technical exposures, and tactical decisions players must make across various sports (Table 2.1). For example, in adolescent football players it has been demonstrated that altering the size of the pitch for SSG influences factors such as shot selection, zone defence, and goalkeeper actions [79, 80]. Further, there is conflicting research on the effect of pitch size on technical actions in Rugby League, with some studies reporting no effect of pitch size [81], whilst others found that smaller pitches increased the number of technical exposures in adolescent athletes [82]. There has been no research reporting the effect of pitch dimensions or player numbers on technical or tactical outcomes in adolescent Rugby Union players [42]. Therefore, there is evidence that altering the task constraints such as pitch size or player numbers may alter the technical and tactical actions, however these constraints have not been fully explored.

Table 2.1. Examples of manipulation of task constraints during SSG and the effect on tactical and technical demands in adolescent athletes

Reference	Task Constraint	Constraint manipulation	Sport	Effect on tactical and technical demands
[81]	Pitch size	W: 10, L:40m ×. W: 40, L:70m	Rugby League	No effect of pitch size on technical demands.
[83]	Pitch size	W: 44m, L:62m ×. W: 35m, L:50m × W: 23m, L:32m	Football	Increasing pitch size reduced intercepts and dribbles, with no effect for any other technical skills.
[84]	Court size	Half court × Full court	Basketball	Increasing court size reduced technical demands.
[85]	Player numbers	10 vs. 10 × 13 vs. 13	Rugby League	Reducing player numbers increased offensive and total skill involvements.
[86]	Player numbers	3 vs. 3 × 4 vs. 4 × 6 vs. 6	Football	Reducing player numbers increased cross, dribbles and shots on goal
	Pitch Size		Football	
	Pitch Size		Football	

Pitch Size	Football
Pitch Size	Football

The physical demands placed on players during SSGs will also change as a result of alterations of task constraints. Physical demands are commonly assessed through tools such as GNSS and heart rate monitors. The effect of manipulating task constraints on physical demands has been extensively explored across several sports (Table 2.2). Generally, increasing size of the pitch and decreasing player numbers was shown to increase the physical demands of SSG across sports such as football, basketball, and rugby league. However, some studies found no effect for pitch size [87]. An additional task constraint that has previously been explored in adolescent athletes was the manipulation of rules. For example, it has been found that policing of off-side, and the inclusion of wrestling or contact within a SSG altered the physical demands [88-90].

Table 2.2. Examples of manipulation of task constraints during SSG and the effect on physical demands in adolescent athletes

Reference	Task Constraint	Constraint manipulation	Sport	Effect on physical demands
[81]	Pitch size	W: 10 x L:40m vs. W: 40 x L:70m	Rugby League	Increasing pitch size increased total distance, moderate, high and very high speed distance, and reduced low speed and very low speed distance.
[87]	Pitch size	W: 36m, L: 27m × W: 40m, L: 29m	Football	No effect of pitch size on physical demands.
[83]	Pitch size	W: 44m x L:62m vs. W: 35m x 50m vs. W: 23m x 32m	Football	Increasing pitch size increased total distance, maximum velocity, low, medium, and high intensity running and sprint frequency.
[84]	Court size	Half court vs. Full court	Basketball	Increasing court size increased average and max heart rate ($p < 0.05$)
[91]	Player numbers	4 vs. 4 × 6 vs. 6	Rugby League	Heart rate was higher in the 4 vs. 6 than 6 vs. 6 condition for U16, but not U13

[91]	Pitch size	4 vs. 4 × 6 vs. 6	Rugby League	Heart rate was higher in the 4 vs. 6 than 6 vs. 6 condition for U16, but not U13
[88]	Rules	Onside vs. Offside	Rugby League	Off-side touch had greater total distance, accelerations, and low, moderate and high velocity distance.
[89]	Rules	Wrestling vs. Touch	Rugby League	No wrestling had greater total distance, low, moderate, high and very high-speed distance, and reduced accelerations, and high-intensity bouts.
[90]	Rules	Contact vs. non-contact	Rugby league	Non-contact games had greater reductions in total distance, and low speed distance.
[92]		1 vs. 2 vs. 3 5 second contact bouts	Rugby League	Increasing contact efforts reduced running intensity.
[93]	Time	1 x 24min vs 2 x 12min vs 3 x 8min vs 4 x 6min vs 6 x 4min vs. 8 x 3min vs	Rugby League	High and moderate speed running and rate of decline in high speed movement increased in the 24 x 1min game, while low speed running decreased.

12 x 2min vs

24 x 1min

Changing task constraints will also manipulate the psychological demands being placed on players during SSG. Three studies have investigated the effect of constraint manipulation on psychological demands (Table 2.3). All three studies were in rugby codes and investigated the effect of rule manipulation. It was found that rules could be changed to deliberately target certain psychological demands, for example, deliberately frustrating players by altering the referee's adjudication of the laws [94, 95]. Further, on-side touch had greater cognitive RPE than off-side touch [88]. However, there is no research in Rugby Union on the effects of manipulating common task constraints, such as pitch size and player numbers, on the psychological demands placed on adolescent athletes.

Table 2.3. Examples of manipulation of task constraints during SSG and the effect on psychological demands in adolescent athletes

Reference	Task Constraint	Constraint manipulation	Sport	Effect on tactical and technical demands
[95]	Rules	Rules manipulated to target physical, mental, frustration, temporal and technical demands	Touch Rugby	Rules manipulated to deliberately target a subscale of the NASA-TLX successfully manipulated that outcome ($\eta^2 = 0.118–0.211$, $p < 0.001$)
[94]	Rules	Rules manipulated to target physical, mental, frustration, temporal and technical demands	Rugby Union	Rules manipulated to deliberately target a subscale of the NASA-TLX successfully manipulated that outcome ($\eta^2 > 0.1$)
[88]	Rules	Onside vs. Offside touch	Rugby League	Cognitive RPE was greater during on-side games ($p < 0.05$).

2.4 Summary

This chapter has provided a non-exhaustive review of the literature relevant to models of youth athletic development, load monitoring, and small-sided games in adolescent athletes. A brief summary of the findings of this chapter are included below.

- Models of adolescent athletic development emphasise the need to develop all physical qualities, as well as sports specific skills.
- Strength is an important physical quality for athletes across all stages of their athletic career, including adolescence. Therefore, valid, and reliable methods of assessing strength are required.
- There has been significant research on the training load of adolescent athletes, however, the methods of monitoring training load and their relationship to outcome measures are yet to be systematically reviewed and synthesised.
- Logistic and linear regression models are commonly used to assess relationships between training load and outcomes measures, however, are bound by strict assumptions, such as normality of residuals and multicollinearity.
- Dimension reduction techniques and feature selection algorithms may present alternative statistical techniques to assess the load-response relationship. Furthermore, feature selection algorithms, whilst novel in a sporting context, may be more easily interpreted.
- SSG are a commonly used training drill, that facilitates development of tactical, technical, physical and psychological development.
- The primary method to alter SSG is through alteration of task constraints, with pitch size and player numbers being commonly manipulated.
- No research to date has examined the manipulation of pitch size and player numbers on the technical, physical, and psychological demands in adolescent Rugby Union players.

Chapter 3. General Methods

This chapter will detail commonly used (i.e., two or more times) data collection and statistical analysis methods within this thesis. Initially, the experimental approach to the problem and a background on the industry partner will be provided. Following this, details will be given on the participant recruitment methodology and common procedures used throughout the thesis. Finally, this chapter will provide an overview on the statistical considerations used for analyses. The methodologies specific to the individual studies will be outlined in the relevant chapters.

3.1 Experimental approach to the problem

Four studies were be conducted to either 1) Evaluate the training practices, both resistance and field-based training and assess the changes in physical characteristics, of adolescent athletes; or 2) Assess the validity and reliability of the IMTP; or 3) Evaluate the effect of manipulating task constraints on the physical, technical and subjective task-load demands in SSG.

Table 3.1 Description of study aims and designs

Study	Aim	Research Design	Data Collected
1. Methods of monitoring internal and external load and relationship to changes in physical qualities, injury, or illness in adolescent athletes?: A systematic review and best-evidence synthesis	The purposes of this study were to (1) systematically examine the current literature reporting the training load monitoring methods used in adolescent athletes and (2) systematically examine the current literature reporting the relationship between training loads and changes in physical qualities, injury and illness.	Systematic review and best-evidence synthesis	Training load monitoring tools used and relationships between training loads and changes in physical qualities, injury and illness.
2. Training practices of adolescent athletes and relationship to changes in physical qualities	The purposes of this study were to (1) quantify the distribution of training loads, both field and resistance training, in adolescent rugby players, and (2) assess the relationship between training loads and changes in physical qualities in adolescent rugby players.	Longitudinal, observational study with relationships between training loads and physical changes, stress and recovery identified.	Anthropometrics, maturation level, strength (IMTP and Bench Press 2-6RM), lower body power (Countermovement Jump), speed (10m and 40m), perceived intensities, volume loads, GNSS data, and subjective stress and recovery.
3. The effect of isometric mid-thigh pull grip on the validity and reliability of outcome measures	The purpose of this study was to assess the inter-day reliability and validity of different grips in the IMTP	Within-participants, between day reliability and validity.	Peak force, rate of force development, and impulse.
4. Effect of pitch size and player number manipulation on the physical, technical, and subjective task-load demands in SSG.	The purposes of this study was to (1) investigate the effect of pitch size manipulation on technical, physical, and subjective task load demands in SSG in adolescent Rugby Union, and (2) investigate the effect of player number manipulation on technical, physical, and subjective task load demands in SSG in adolescent Rugby Union.	Crossover study	GNSS Data, heart rate data, NASA TLX, perceived intensities, and technical involvements.

3.2 Industry partner

This thesis was conducted as part of a co-funded scholarship with St. Joseph's Nudgee College. The college is an independent, all-male school in South East Queensland, with a strong reputation for sporting and academic success. The college educates adolescent athletes, typically aged 11 – 18 years, and competes in the Great Public Schools Association of Queensland sports competition. Sports participated in by the college are Rugby Union, Basketball, Rowing, Track and Field, Football, Tennis, Cricket, Volleyball, Track and Field, and Swimming. The college's sporting reputation is exemplified by its achievement of 44 Rugby Union premierships, a figure more than double that of the next closest school. There is already an established Strength & Conditioning program at the school, which influenced some of the methodologies and decisions surrounding data collection. The motivation of the college in co-funding this thesis was to ensure their strength and conditioning department was offering a current model in the assessment and manipulation of training load in their student athletes.

3.3 Recruitment

Throughout the thesis, 81 participants have been recruited to participate. Due to feasibility, and reliability of force expression related to training age rather than chronological age, study three was conducted on adult populations, and thus recruitment occurred through advertisement. Participants in studies two and four were recruited from within the college. Initially, the Director of Sport for each individual sport identified individuals within the program, who meet the inclusion criteria and may wish to volunteer within the study. Following this, participants and their parents were sent a participant information letter and consent form via email. After participant assent and guardian consent was obtained, data collection procedures began.

3.4 Ethical Considerations

This program of research consisted of projects which were granted approval by the Australian Catholic Universities Human Ethics Review Board. As study one was a systematic review, no ethical approval was required. Studies two (2020-1362), three (2021-217HE), and four (2022-2717H) were all granted ethical approval. Whilst a convenience sample of participants were approached to volunteer in these studies, participation in the research was entirely voluntary. Additionally, no benefit with regards to team selection was afforded to those who volunteered. To reduce risk of coercion, participants in study three were contacted through the Director of Athletic Development as opposed to the student researcher. Further ethical considerations included the recruitment of minors to participate within the study. As such, participant assent and parental consent was sought prior to commencement. Other ethical considerations that were present in this program of research included the possibility of muscular strains and sprains, as studies 2-5 involved physical exertion. To reduce the risk of injury, all participants completed warmups, and were familiar with the protocols used.

3.5 Common procedures and outcome measures

Throughout this thesis, several different testing, and data collection procedures and outcome measures were used. To facilitate ease of reading, the following section details the procedures used at least twice throughout the thesis. Several variables, such as assessments of physical qualities, were both dependent and independent variables dependant on which research aim was being investigated.

Standing height, sitting height

Participant height was recorded using a stadiometer (Design No.1013522, Surgical and Medical Products, Seven Hills, Australia). Participants removed their shoes and stood facing away from the device and were instructed to keep their head level. Upon inhalation, the researcher adjusted the measuring device until it touched the participants head and was parallel to the floor. Seated height was measured by the participant sitting on a box, with the height of the box (31cm) then subtracted from the final result. Heights were recorded to the nearest 0.1cm. The standing height and seated height measurements were used to approximate level of maturation using the Mirwald equation (Equation 1) [96].

Equation 1. Mirwald

$$-9.236 + 0.0002708 \times (\text{LegLength} \times \text{SeatedHeight}) - 0.001663 \times (\text{Age} \times \text{LegLength}) .+ 0.007216 \times (\text{Age} \times \text{SeatedHeight}) + 0.02292 \times (\text{weight} \div \text{StandingHeight})$$

Isometric Midthigh Pull

In study two, the IMTP was used to assess the ability to produce force. In study three, the validity and reliability of different methods of performing the IMTP was assessed. This was performed to validate the methodology used in study two. Participants completed the IMTP on a force plate (ForceDecks, Vald, Brisbane, Australia). Bar height was adjusted to obtain knee and hip angles of 125 – 145° and 140 - 150°, respectively [37]. Participants were instructed to maintain an upright torso, with shoulders slightly retracted and depressed [37]. Participants used an overhand grip, with either no straps or tape (study three), figure 6 liftings straps and rigid tape (Beiersdorf Australia LTD, Sydney, Australia) (study three), or figure eight lifting straps (Loaded Lifting, Perth, Australia) (studies 2 and 3) to ensure a firm grip on the bar (Figure 3.1) [37].

Figure 3.1. Figure six (A) and Figure eight (B) lifting straps

Previous research detailing the methodological considerations for the IMTP instructs that standard "loop" lifting straps, and tape be used to secure athletes to the bar. However, this methodology was not feasible in the applied environment, and therefore the validity and reliability of the use of figure eight straps was explored in study two. To begin, participants took the slack out of the bar, and the live force-time trace was visually inspected to ensure a stable baseline. Participants were given an audible countdown – "On go, pull as hard and fast as possible. 3, 2, 1, GO! Pull, Pull, Pull". Participants completed warm up trials of 3 x 3 seconds at 50%, 75% and 90% perceived effort [37]. Trials were considered successful if a stable baseline, and no countermovement was detected [37].

Following collection, force-time data were downloaded from ForceDecks software and exported into RStudio (Version 1.1.383, RStudio, Boston, MA) for analysis using custom code (Appendix 1). Analysis through RStudio was performed as ForceDecks software does not describe, or allow alteration to, the method to ascertain onset. It has previously been described that onset should be identified as the point in time in which force is greater than five times the standard deviation of force during the stable baseline period [37]. Different methods of calculating onset have been shown to effect time-bound metrics, such as rate of force development and impulse [97]. Additionally, whilst visual inspection of the force-time trace was performed live to identify successful trials, and therefore the potential need for additional trials, further analysis was performed through R to confirm trials did not have a countermovement, and achieved a stable baseline. A countermovement was identified if, following the stable baseline period, force reduced by the magnitude of the onset threshold. A stable baseline was identified as the latest one second period in which the total change in force was less than 50N [37].

2km time trial

To assess aerobic fitness, participants completed a 2km running time trial in studies two and four. The 2km time trial was selected as it has previously been shown to have strong relationships to maximal aerobic speed [98] and is highly reliable, when measured with handheld stopwatch (CV 1.9%; ICC 0.95) [99]. Maximal aerobic speed is the speed required to elicit maximal oxygen consumption, and is commonly used to prescribe training loads [98]. Time was assessed via a hand-held stopwatch (Regent 240 Econo Sports Stopwatch, Regent, Victoria, Australia) and manually recorded. All participants were encouraged to give a maximum effort throughout the 2km trials. To begin the 2km trial participants were given a “Ready” call, followed by a short whistle blast. The test took place on a dry, outdoor running track.

40m Sprint

In studies two and four acceleration and speed were assessed using a 40m linear sprint. Sprint times were measured using single beam timing system (TC Photogate; Brower timing systems, Draper, UT, USA) that has been previously shown to be reliable for both 10m (CV: 2.5% (90%CI 2.1-3.5)) and 40m (CV: 1.8% (90%CI 1.5 – 2.3)) [100] in adolescent athletes. Additionally, in study four, maximum velocity was assessed using GNSS devices (Optimeye S5 or Catapult X4, Catapult Sports, VIC, Australia). were set up at 0, 10 and 40m splits, with all gates height set at 60cm [101]. A 10m split was used to assess acceleration, and the 40m split was used to assess maximum speed. The test was completed on an outdoor running track. The test was completed on an outdoor running track. Subjects were instructed to take a 2-point stance 30cm behind the first gate, indicated with a cone, and self-initiated the start of the sprint [102].

Global navigation satellite systems (GNSS) data

In studies 2 and 4, assessment of external locomotive demands was conducted with a 10 Hz GNSS device (Optimeye S5 or Catapult X4, Catapult Sports, VIC, Australia) secured to their thoracic region using a fitted bib or guernsey with a GNSS pocket. 10 Hz GNSS devices have been previously shown to be valid methods of assessing the primary variables of interest (Table 1). [29, 103]. Data was collected and transmitted to an online cloud-based platform, before being downloaded to custom-built spreadsheets (Microsoft Excel 2016, Microsoft Corporation, Redmond, USA).

Table 3.2. Reliability of GPS metrics [104]

Variable	CV%
Total Distance	1.5% ± 1.6%
Max Velocity	0.3% ± 1.6%
Low speed running ($<3\text{m.s}^{-1}$)	4.4% ± 1.6%
Medium speed running ($3 – 5\text{m.s}^{-1}$)	0.3% ± 1.6%
High speed running ($> 5\text{m.s}^{-1}$)	0.% ± 1.6%
High accelerations (1m.s^{-2})	5.9% ± 1.6%
Moderate accelerations (2m.s^{-2})	2.3% ± 1.6%
Low accelerations (3m.s^{-2})	3.2% ± 1.6%

S*ession ratings of perceived exertion*

In studies 2 and 4, a session rating of perceived exertion (sRPE) scale was used to assess the internal training load. Session rating of perceived exertion is a method of quantifying perceived internal training load [28]. sRPE is widely used as it is cheap, and simple to collect, and is a reliable measure of exercise intensity across a variety of training modalities, such as resistance training [105] and field-based training [106]. Additionally, reporting of sRPE has been shown to be valid up to 24 hours post training in adolescent athletes [106].

To assess the perceived internal response to training load, participants were instructed to complete a sRPE questionnaire using the Borg category-ratio 10 scale, which has been previously validated in adolescent athletes (Figure 3.2) [106]. To allow participants to report both in-school and outside of school training load, separate questions were provided daily. Additionally, participants reported resistance training load sRPE separately from field training load. This data was used to provide daily training loads, as well as the distribution between in college field and resistance training, and structured training outside of the college. In study two, sRPE's were collected using TeamBuildr, at least 15-30 minutes following the training session. In study four, sRPE's were manually recorded by each individual immediately following the experimental condition.

How was your workout
0 = Rest
1 = Very easy
2 = Easy
3 = Moderate
4 = Somewhat Hard
5 = Hard
6 =
7 = Very Hard
8 =
9 =
10 = Maximal

Figure 3.2. Borgs Category-Ratio 10 Scale [106]

Chapter 4. Study One - Methods of monitoring internal and external loads and their relationships with physical qualities, injury, or illness in adolescent athletes: A systematic review and best-evidence synthesis

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4.1 Introduction

Training and physical activity is integral for physical development [107]. When an athlete completes a training session, there is an acute increase in fatigue, which, with recovery, is then typically followed by a supercompensatory response [18]. Improving physical qualities has previously been shown to improve physical performance [108, 109], decrease injury risk [110], improve recovery [22] and influence selection [111] in team sports, and therefore forms a significant focus of the training process. However, without adequate recovery following training, the athlete may suffer decreased performance and potentially injury or illness [112, 113]. This relationship was originally referred to as the General Adaptation Syndrome [18], and despite this model having undergone refinement [114], the principle of providing a sequentially greater training stimulus, followed by adequate rest and recovery, remains the premise on which most modern training programs are based upon. Colloquially, this balance between fitness and fatigue has been termed the "goldilocks effect" and highlights the need to understand both the positive and negative responses to training load [115].

To ensure appropriate prescription of training and rest, load monitoring programs are often implemented, particularly in elite sport [30]. However, with the increasing professionalisation of youth sports, greater emphasis is being placed on quantifying the training loads of adolescent athletes [32, 56, 116]. There are both internal and external methods of monitoring training loads. External methods of monitoring load measure the work performed by an athlete, including resistance training volume load (sets × reps × load) and running metrics through global navigation satellite systems (GNSS) [29]. Alternatively, internal load monitoring methods capture the physiological (e.g., heart rate; HR) and psychophysiological (e.g., session rating of perceived exertion; sRPE) responses to the external load [29]. In comparison to external load, internal load is a more accurate measurement of the individualised response to training stress [117]. However, it is challenging to prescribe training based off internal load, as it is influenced by numerous factors, for example, hydration status [118]. Therefore, it is often more practical to prescribe training based on external loads. Given the limitations of internal and external load metrics, both internal and external loads will often be integrated in a load monitoring regime.

Throughout adolescence, an athlete's response to training load will change due to factors such as maturation and training exposure [12], and therefore they are likely to have fluctuating responses to training load. For example, changes in sex hormones throughout maturation facilitate greater strength and hypertrophy adaptations [12, 119]. Given the unique environment of adolescent athletic development, multiple attempts at developing training models to optimise adolescent athletic development have been proposed, such as the long-term athlete development model [1] and the youth physical development model [2]. These models propose that the development of certain physical qualities should be emphasised at different points throughout maturation. This highlights the need for a systematic review of the literature to understand the current evidence of complex nature of the load-response relationship in adolescent athletes.

Given the increased focus on training load monitoring in adolescent athletes, a systematic review of the literature is appropriate to guide practitioners and researchers on the relationship between methods of monitoring training load and physical qualities, injury, or illness. Subsequently, the aim of this systematic review was to detail the methods of reporting internal and external loads in adolescent athletes and describe their relationship with changes in physical qualities, injury, or illness.

4.2 Methods

4.2.1 Design and Search strategy

This review was registered via PROSPERO (CRD42021245503). An electronic search was conducted of the CINAHL, SPORTdiscus, Web of Science and SCOPUS databases. Search terms and strategy are reported in Table 4.1. Search terms were crafted by reviewing known original research and reviews relevant to the topic [120]. No searches were mapped to medical subject heading terms. The search strings were initially searched independently and then combined with AND. Strings were adjusted based on database-specific truncation, wildcard, and proximity operators. The search was restricted to studies published in English. Articles were retrieved from the earliest possible date until March 2022.

Table 4.1. Search terms used

Variable	Search strings
Adolescent	Adolescen* OR teen* OR Pubescent OR junior OR “School athlet*” OR youth* OR “Under#11” OR “Under#12” OR “Under#13” OR “Under#14” OR “Under#15” OR “Under#16” OR “Under#17” “Under#18” OR “Under#19”
Athletes	archer* OR athlete* OR baseballer* OR basketballer* OR batsm?n OR boarder* OR bobsledder* OR bowler* OR boxer* OR canoeist* OR cricketer* OR cyclist* OR dancer* OR footballer* OR golfer* OR gymnast* OR handballer* OR hurdler* OR jockey* OR kayaker* OR marathoner* OR netballer* OR orienteer* OR racewalker* OR rower* OR Rugby OR sailor* OR skater* OR skier* OR softballer* OR sportsm?n OR sportspeople OR sportsperson* OR sportswom?n OR sprinter* OR swimmer* OR volleyballer* OR weightlifter* OR wrestler* OR “badminton player*” OR “baseball player*” OR “basketball player*” OR “football player*” OR “handball player*” OR “hockey player*” OR “lacrosse player*” OR “martial artist*” OR “netball player*” OR “race walker*” OR “soccer player*” OR “softball player*” OR “squash player*” OR “tennis player*” OR “volleyball player*” OR “water polo player*” OR “weight lifter*” OR *rider* OR *runner*
Load monitoring	"Training load*" OR "Physical load*" OR "work load*" OR load* OR "Training practice*" OR "Global workload index" OR "NASA-TLX" OR "*RPE" OR "Perceived Exertion" OR trimp OR GPS OR "Training volume" OR "Training frequency"
Physical qualities	perform* OR fitness OR strength OR power OR cognitive OR aerobic OR skills OR physiolog* OR Jump OR physical) N5 (TI,AB,SU Measure* OR assess* OR test* OR utility OR instrument* OR checklist* OR questionaire* OR capacity OR perform* OR qualities
Injuries and illness	injur* OR Illness OR “Upper respiratory tract infection” OR URTI
NOT	“systematic review” OR “Rat”

4.2.2 Inclusion and Exclusion Criteria

The preferred reporting items for systematic review and meta-analyses (PRISMA) guidelines were followed to screen articles [121]. Article screening was performed by CD and JW; a third reviewer (RJ) was used to solve any conflicts. Inclusion criteria were original research investigations, full-text articles written in English, published in a peer-reviewed academic journal, with participants aged 10–19 years old who participated in competitive sport [9]. Competitive sport was defined as any game or activity that involves physical exertion and skill, played against other teams or individuals [7]. Additionally, all studies were required to report a statistical relationship between a measure of internal or external training load and physical quality, injury or illness. Manuscripts were excluded if they were commentaries, letters, editorials, conference proceedings, case reports, conference abstracts or non-peer reviewed articles and studies with <1 week of load monitoring or alterations to load such as “Shock periods” [122].

Both observational and intervention-based studies were included, provided there was an indication of the relationship between load and change in physical quality, injury, or illness. Load was defined as “the cumulative amount of stress placed on an individual from multiple training sessions (structured or unstructured) over a period of time.” [123]. Physical quality was defined as any test of an element of fitness, such as strength, power, endurance, or speed. Illness was defined as any non-musculoskeletal medical reporting event. Additionally, injury was defined as a medical reporting event, whether or not it resulted in time loss [124]. Due to various methods of reporting injury and illness data, the definitions were deliberately kept broad. Finally, studies were included if they reported either the incidence or burden of injury (hours or sessions of training lost).

4.2.3 Assessment of study quality

A modified Downs and Black [125] checklist was used to assess methodological quality by a single reviewer (CD); if clarification was required for any of the studies, a second reviewer was consulted (JW). This checklist has previously been used in sport science systematic reviews that similarly included a variety of study designs [126]. Items were scored as 1 (yes) or 0 (no or unable to determine), with a maximum score of 12.

4.2.4 Data extraction & analysis

Data were extracted by CD from included studies into a custom Google spreadsheet (Alphabet, Mountain View, CA). Extracted data included participant characteristics such as age, stature, body mass, maturation level (if reported), sport and playing level. The study results extracted were the method of monitoring the training load, and the measurement of either change in physical quality, injury, or illness. Statistical interpretations of the results were only provided if reported in the original research. Contributing findings included in the best-evidence synthesis were any reported statistical relationship from included studies. Unclear data were reported, but not included in the best-evidence synthesis. Assessments of physical qualities were grouped into relevant categories, being strength, power, aerobic fitness, repeated sprint ability, flexibility, muscular endurance, and change of direction. Studies included in this systematic review included a number of different study types (i.e. intervention and observational) and different statistical methods (i.e. correlation, hypothesis testing, effect sizes). As such, the heterogeneity of the results precluded meta-analysis, therefore data were synthesised according to the following criteria [120, 127]:

Strong evidence: Consistent findings across two or more studies, and at least 75% of all contributing findings.

Moderate evidence: Consistent findings across two or more studies, and at least 50% of all contributing findings.

Limited evidence: Consistent findings identified in one study, and at least 50% of all contributing findings.

Inconsistent evidence: Conflicting findings across multiple studies, or less than 50% of contributing findings.

No evidence: No changes reported.

4.3 Results

4.3.1 Search findings and study selection

The search results are highlighted in Figure 4.1. 85 full-text articles were screened, with 59 studies included in the final review.

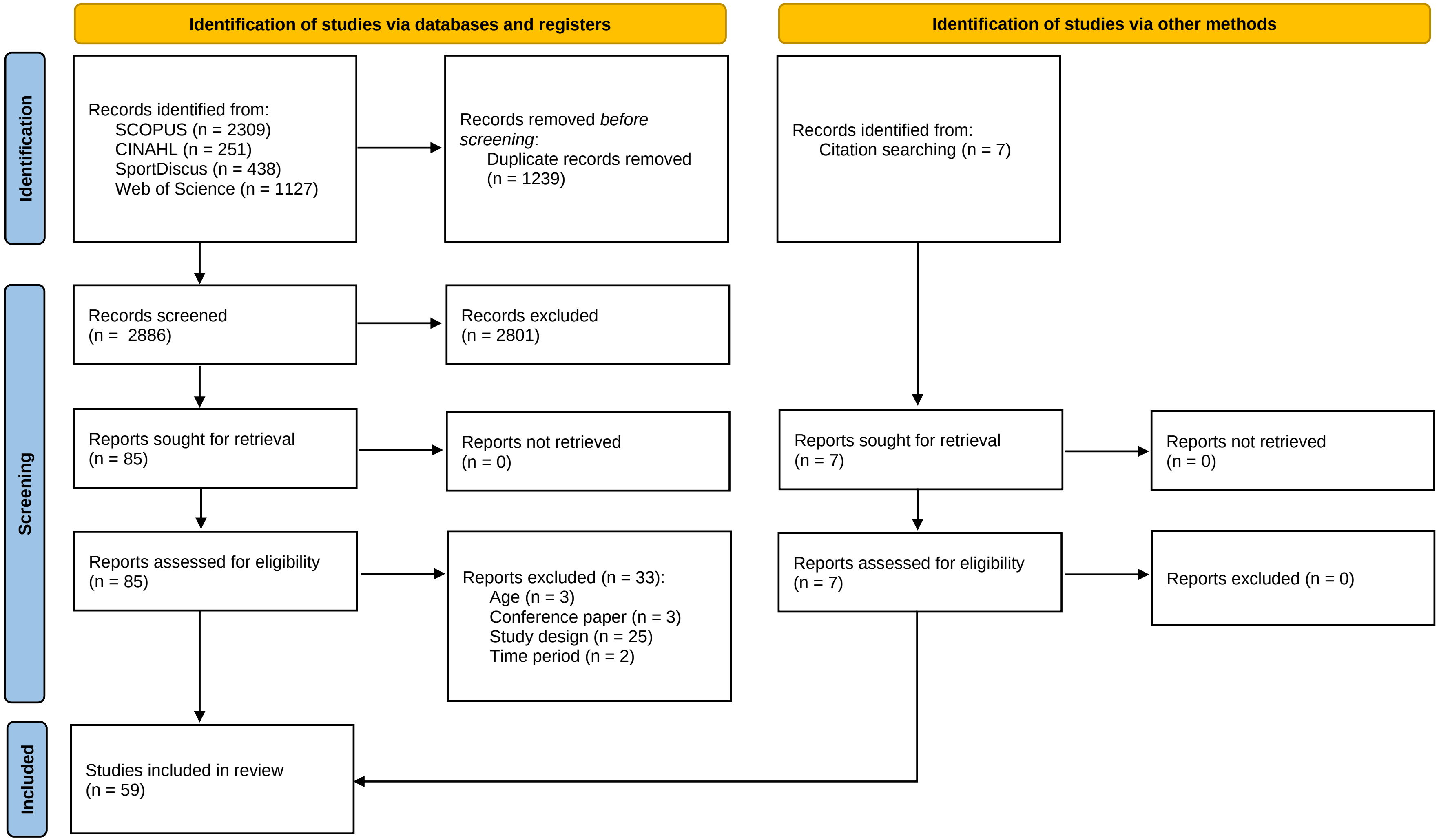

Figure 4.4. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) flow diagram of search strategy

Methodological scores ranged from 6 to 11 with a mean of 8.4 ± 1.4 out of 12 (Table 4.2). No articles were excluded on the basis of methodological quality.

Table 4.2. Results of modified Downs and Black for included studies

References	**Reporting**			**External Validity**			**Internal validity bias**			**Power**			**Total**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
Ahmun et al., [128]	1	1	1	1	1	1	0	1	1	1	1	0	10
Akubat et al., [63]	1	1	0	1	1	0	0	0	1	1	1	0	7
Albrecht et al., [129]	0	1	1	1	1	1	0	0	1	1	1	0	8
Antualpa et al., [130]	1	1	1	1	1	1	0	0	1	1	1	0	9
Bacon and Mauger [131]	1	1	1	1	1	1	0	0	1	1	1	0	9
Bowen et al., [132]	0	1	1	1	0	0	0	0	1	1	1	0	6
Brink et al., [133]	0	1	1	1	1	0	0	0	1	1	1	0	7
Brink et al., [134]	1	0	0	1	1	0	0	0	1	1	1	0	6
Brisola et al., [135]	1	1	1	1	1	0	0	0	1	1	1	1	9
Brunelli et al., [136]	0	1	1	1	1	1	0	0	1	1	1	0	8
Cahalan et al., [137]	0	1	0	1	1	1	0	0	1	1	1	0	7
Chaabene and Negra, [138]	0	1	1	1	1	1	0	0	1	1	1	0	8
Delecroix et al., [139]	0	1	1	1	1	1	0	0	1	1	1	0	8
Dobbin et al., [140]	0	1	1	1	1	1	0	0	1	1	1	0	8
Ellis et al., [64]	0	1	1	1	1	0	0	0	1	1	1	0	7
Fett et al., [141]	0	1	1	1	1	0	0	0	1	1	0	0	6
Figueiredo et al., [65]	1	1	1	1	1	1	1	1	1	1	1	0	11
Figueiredo et al., [142]	1	1	1	1	1	1	0	0	1	1	1	1	10
Fitzpatrick et al., [66]	1	1	1	1	1	1	0	0	1	1	1	0	9
Fleisig at al., [143]	1	1	0	1	1	1	1	1	1	1	1	0	10
Freitas et al., [144]	1	1	1	1	1	0	0	0	1	1	1	0	8
Gil-Rey et al., [145]	1	1	1	1	1	1	0	1	1	1	1	0	10
Gonzalez-Badillo et al., [146]	1	1	1	1	0	1	0	0	1	1	1	0	8
González-Badillo et al., [147]	1	1	1	1	0	1	0	0	1	1	1	0	8

Hartwig et al., [148]	0	1	1	1	1	1	0	0	1	1	1	0	8
Huxley et al., [149]	0	1	0	1	1	1	1	0	1	1	0	0	7
Johannsson et al., [150]	1	1	1	1	1	1	1	1	1	1	1	0	11
Johansson et al., [151]	1	1	1	1	1	1	1	1	1	1	1	0	11
Jones et al., [152]	0	1	1	0	1	1	1	1	0	0	0	0	6
Kiernan et al., [153]	0	1	1	0	0	1	0	0	1	1	1	0	6
Lathlean et al., [154]	1	1	1	1	1	1	1	1	1	1	1	0	11
Lopez Segovia et al., [155]	0	1	1	1	1	0	0	0	1	1	1	0	7
Lyman et al., [156]	0	1	0	1	0	1	1	1	1	1	1	1	9
Martínez-Silván et al., [157]	0	1	1	1	0	0	0	0	1	1	1	0	6
Mehta et al., [158]	1	1	1	1	1	0	1	1	1	1	1	1	11
Møller et al., [159]	1	1	1	1	1	1	1	0	1	1	1	0	10
Moreno-Pérez et al., [160]	0	1	1	1	1	1	0	0	1	1	1	1	9
Murphy et al., [161]	1	1	1	1	1	0	0	0	1	1	1	0	8
Murphy et al., [162]	1	1	1	1	1	0	0	0	1	1	1	0	8
Myers et al., [163]	1	1	1	1	1	1	0	0	1	1	1	0	9
Nobari et al., [164]	0	1	0	1	1	1	0	0	1	1	1	0	7
Nobari et al., [165]	0	1	1	1	1	1	0	0	1	1	1	1	9
O'Keeffe et al., [166]	0	1	1	1	1	1	0	0	1	1	1	0	8
Otaegi and Arcos, [167]	0	1	1	1	1	1	0	0	1	1	1	0	8
Patel et al., [168]	1	1	1	1	1	1	1	0	1	1	1	0	10
Post et al., [169]	1	1	1	1	1	1	0	0	1	1	1	0	9
Post et al., [170]	1	1	1	1	1	1	0	0	1	1	1	0	9
Prieto-González et al., [171]	1	1	0	1	1	1	1	1	1	1	1	0	10
Pullinger et al., [172]	1	1	1	1	0	1	0	0	1	1	1	0	8
Purnell et al., [173]	0	1	1	1	0	1	0	0	1	1	1	1	8
Raya-González et al., [174]	1	1	1	1	1	0	0	0	1	1	1	1	9
Sawczuk et al., [175]	0	1	1	1	1	0	0	0	1	1	1	0	7
Sugimoto et al., [176]	1	1	1	1	1	1	0	0	1	1	1	0	9
Taylor et al., [177]	0	1	1	1	1	1	0	0	1	1	0	0	7
Visnes and Bahr, [178]	0	1	1	1	1	1	0	1	1	1	1	0	9
Von Rosen et al., [179]	1	1	1	1	1	0	0	1	1	1	1	0	9
von Rosen et al., [180]	1	1	1	1	1	1	0	1	1	1	1	0	10

Watson et al., [181]	0	1	1	1	1	1	0	1	1	1	1	0	9
Weakley et al., [31]	1	1	1	1	1	1	0	0	1	1	1	0	9

Participant characteristics are presented in Table 4.3**.** Sports included cricket (n = 1), soccer (n = 19), multi-sports (n = 6), water polo (n = 1), basketball (n = 2), Irish dancing (n = 1), rugby league (n = 1), tennis (n = 7), weightlifting (n = 2), track & field (n = 4), baseball (n = 3), Australian football (n = 1), Gaelic football (n = 1), table-tennis (n = 1), gymnastics (n = 3), Rugby Union (n = 3), volleyball (n = 1), and orienteering (n = 2). Year of publication ranged from 2002 to 2022, with 88% of studies published since 2012. Sample sizes ranged from eight to 2011 athletes (total = 8935; median = 35). In total, 35 studies investigated males, five investigated females, 18 investigated both males and females, and one did not state sex. The reported mean age of the participants ranged from 13.4 to 18.8 years. 24 studies assessed internal load response, 27 assessed external loads, and eight assessed both internal and external loads. The most commonly reported internal load monitoring tools were sRPE (n = 29) and heart rate (n = 7). The most commonly reported external load monitoring tools were training duration (n = 22) and GNSS (n = 5). Physical qualities investigated included strength (n = 5), aerobic fitness (n = 19), speed (n = 12), power (n = 3), change of direction (n = 7), flexibility (n = 1), muscular endurance (n = 1) and repeated sprint ability (n = 3). Additionally, 34 studies investigated injury, and six studies investigated illness.

Table 4.3. Study and participant characteristics

Reference	Year	Sport & Level	Sample size	Age	Sex	Stature (cm)	Weight (kg)	Monitoring tool	Outcome of interest
Akubat et al., [63]	2012	Professional soccer	9	17.0 ± 1	Male	181.0 ± 5.0	72.9 ± 6.7	sRPE Heart rate	Physical quality
Brink et al., [133]	2010	Professional soccer	18	17.0 ± 0.5	Mate	180.0 ± 7.3	72.4 ± 7.8	sRPE	Physical quality
Brisola et al., [135]	2020	National water polo	20	15.7 ± 1.3	Female	162.0 ± 10.0	60.9 ± 11	sRPE	Physical quality Illness
Chaabene and Negra, [138]	2017	Academy soccer	25	12.7 ± 0.2 (LPT) 12.7 ± 0.3 (HPT) 14.3 ± 0.3 (LPT APHV) 14.3 ± 0.8 (HPT APHV)	Male	157.2 ± 3.6 (LPT) 155.9 ± 9.0 (HPT)	42.7 ± 4.7 (LPT) 45.0 ± 8.5 (HPT)	Plyometric volume	Physical quality
Dobbin et al., [140]	2018	Academy rugby league	16	17.2 ± 0.7	Male	179.9 ± 4.9	88.5 ± 10.1	sRPE	Physical quality
Ellis et al., [182]	2020	Academy soccer	9	17.1 ± 1	Male	179 ± 5.6	71.3 ± 5.8	sRPE Heart rate GNSS	Physical quality
Figueiredo et al., [142]	2019	Professional soccer	16	18.7 ± 0.6	Male	175.0 ± 5.6	69.1 ± 6.6	sRPE	Physical quality
Figueireido et al., [65]	2019	Youth Soccer	16	18.8 ± 0.7	Male	175.3 ± 5.5	68.7 ± 6.5	sRPE Heart rate	Physical quality
Fitzpatrick et al., [66]	2018	Professional soccer	14	17.1 ± 0.5	Male	178.3 ± 4.6	70.9 ± 5.8	sRPE GNSS	Physical quality

Gil-Rey et al., [145]	2015	Professional soccer	28	17.6 ± 0.6 (elite) 17.5 ± 0.5 (non-elite)	Male	179.7 ± 5.6 (elite) 178.1 ± 5.6 (non-elite)	70.3 ± 4.4 71.1 ± 6.5	dRPE	Physical quality
Gonzalez-Badillo et al., [146]	2005	National weightlifting	51	16.4 ± 1.3 (Low volume) 16.5 ± 1.4 (Medium volume) 16.8 ± 1.7 (High volume)	Male	167.3 ± 3.9 (Low volume) 166.7 ± 4.1 (Medium volume) 165.4 ± 5.6 (High volume)	72.7 ± 5.4 (Low volume) 70.5 ± 5.7 (Medium volume) 69.4 ± 5.3 (High volume)	Training volume	Physical quality
González-Badillo et al., [147]	2006	National weightlifting	29	17.1 ± 1.7 (Low intensity) 16.9 ± 1.7 (Medium intensity) 17.5 ± 1.9 (High intensity)	Male	168.0.± 4.1 (Low intensity) 167.0 ± 4.0 (Medium intensity) 169.1 ± 3.6 (High intensity)	73.7 ± 5.5 (Low intensity) 74.0 ± 3.9 (Medium intensity) 72.0 ± 2.3 (High intensity)	Training volume	Physical quality
Johansson et al., [151]	2022	Tennis	301	14.5 ± 2.0	Both	169.8 ± 11.2	58.3 ± 12.7	Training volume	Injury
Johansson et al., [150]	2022	Tennis	271	14.6 ± 2.0	Both	169.9 ± 10.9	58.5 ± 12.5	Training volume	Injury
Jones et al., [152]	2021	Middle-distance running	10	16.2 ± 2	Male	173.0 ± 9	55.7 ± 10.1	Training volume Heart rate	Physical quality
Mehta et al., [158]	2022	High-school baseball	49	17.9 ± 0.4	Male	181.8 ± 6.8	80.6 ± 9.1	Throw count	Injury
Lyman et al., [156]	2002	Baseball	476	12.0	Male	152.0	48.0	Throw count	Injury

Fleisig et al., [143]	2011	Baseball	481	12.0 ± 1.7	Male	-	-	Throw count	Injury
Lopez Segovia et al., [155]	2014	Professional soccer	19	18.3 ± 0.6	Male	179.5 ± 6.8	74.4 ± 8.2	Heart rate	Physical quality
Murphy et al., [161]	2015	International tennis	30	17.0 ± 1.3	Both	176.7 ± 6 (male) 170.2 ± 3.8 (female)	66.9 ± 8.6 (male) 60.5 ± 5.5 (female)	sRPE	Physical quality
Murphy et al., [162]	2015	International tennis	30	17.0 ± 1.3	Both	176.7 ± 6 (male) 170.2 ± 3.8 (female)	66.9 ± 8.6 (male) 60.5 ± 5.5 (female)	sRPE	Physical quality
Nobari et al., [164]	2020	Soccer	23	15.5 ± 0.2 1.9 ± 0.3 maturity offset	Male	172.7 ± 4.2	61.3 ± 5.6	sRPE	Physical Quality
Nobari et al., [165]	2021	Soccer	23	15.5 ± 0.2	Male	172.7 ± 4.2	61.3 ± 5.62	sRPE	Physical Quality
Otaegi and Arcos, [167]	2020	Club-level basketball	19	14.9 ± 0.6 (U15) 15.1 ± 0.7 (U16)	Female	161.0 ± 1.0 (U15) 164.0 ± 1.0 (U16)	58.2 ± 7.6 (U15) 62.8 ± 7.2 (U16)	sRPE	Physical quality
Prieto-Gonzaelez et al., [171]	2021	Multi-sport	498	16.4 ± 2.2	Both	-	-	Trainign volume	Injury
Patel et al., [168]	2021	Pathway gymnastics	42	13.4 ± 2.5 (male) 13.1 ± 2.0 (female)	Both	157.7 ± 13.7 (male) 158.1 ± 5.1 (female)	47.8 ± 15.1 (male) 50.1 ± 8.8 (female	sRPE	Injury

Sawczuk et al., [175]	2018	Academy multi-sport athletes	52	17.3 ± 0.6	-	173.0 ± 18.2	73.7 ± 12.6	sRPE	Physical quality
Taylor et al., [177]	2018	Academy Rugby Union	10	18.4 ± 1.0	Male	181.3 ± 5.9	85.9 ± 13.0	sRPE Heart rate GNSS	Physical quality
Weakley et al., [31]	2019	Schoolboy Rugby Union	35	16.9 ± 0.4	Male	178.0 ± 7	80.1 ± 10.5	sRPE Training volume	Physical quality
Ahmun et al., [128]	2019	International cricket	39	17.5 ± 0.8	Male	-	-	sRPE	Injury
Albrecht et al., [129]	2020	School level multi-sports	278	12.1 ± 1.2	Both	-	-	Training volume	Injury
Bacon and Mauger [131]	2017	Professional youth soccer	41	17.8 ± 1.1	Male	175.0 ± 4.5	72.4 ± 3.1	GNSS	Injury
Bowen et al., [132]	2017	Academy football	32	17.3 ± 0.9	Male	180.0 ± 7.3	74.1 ± 7.0	GNSS	Injury
Brink et al., [134]	2010	National soccer	53	16.5 ± 1.2 (season 06/07) 16.5 ± 1.1 (season 07/08)	Mate	177.0 ± 7.8 (season 06/07) 177.3 ± 6.9 (season 07/08)	72.4 ± 7.8	sRPE	Injury Illness
Cahalan et al., [137]	2019	Professional Irish dancing	37	13.0 – 17.0^{b}	4 male 33 female	-	-	Training volume	Injury

Delecroix et al., [139]	2019	Academy soccer	52	16.8 ± 0.9	Male	-	-	sRPE	Injury
Fett et al., [141]	2017	National tennis	166	DC 15.6 ± 1.1 M: RS1 14.9 ± 2.5 F: RS1 14.6 ± 2.1 M: RS2 15.2 ± 0.6	Both	DC 180.7 ± 9.6 M: RS1 171.2 ± 13.9 F: RS1 166.1 ± 10.9 M: RS2 176.3 ± 7.7	DC 69.8 ± 11.7 M: RS1 58.6 ± 15.4 F: RS1 54.1 ± 10.6 M: RS2 62.4 ± 8.7	Training volume	Injury
Hartwig et al., [148]	2019	School and representative Rugby Union	103	15.2 ± 1.5	Male	178 ± 7.4	83.4 ± 9.3	Training volume	Injury
Huxley et al., [149]	2014	Professional track and field	103	17.7 ± 2.4	Both	-	-	Novel subjective scale	Injury
Kiernan et al., [153]	2018	NCAA D1 distance running	9	18.7 ± 1.0	Male	178.4 ± 4.6	629.40± 71.40 (N)	Accelerometer	Injury
Lathlean et al., [154]	2020	Under-18 state league ARF	290	17.3 ± 0.3	Male	188.4 ± 7.1	188.4 ± 7.1	sRPE	Injury
Martínez-Silván et al., [157]	2017	Academy middle-distance running	5	15.7 ± 1.4	Male	174.2 ± 3.2	54.2 ± 4.4	Training volume	Injury
Møller et al., [159]	2017	First division U16 and U18 soccer	679	14.0-18.0	Male	-	-	Training volume	Injury
Moreno-Pérez et al., [160]	2020	Academy tennis	15	17.2 ± 1.1	Both	178.5 ± 8.7	68.1 ± 4.8	sRPE	Injury

Myers et al., [163]	2020	Academy tennis	26	15.0 ± 2.0 16.0 ± 2.0	Both	171.0 ± 3.0 (male) 167.0 ± 2.0 (female)	61 ± 3 (male) 55 ± 3 (female)	sRPE	Injury
O'Keeffe et al., [166]	2020	Club-level gaelic football	97	13.4 ± 1.1	Male	160.0 ± 10.0	59.3 ± 12.5	sRPE	Injury
Post et al., [170]	2017	Multi-sport athletes[a]	2011	13.5 ± 1.6 (low specialisation) 13.7 ± 1.7 (moderate specialisation) 13.8 ± 1.6 (high specialisation)	Both	-	-	Training volume	Injury
Post et al., [169]	2017	High-school athletes	1544	16.1 ± 1.1	Both	-	-	Training volume	Injury
Pullinger et al., [172]	2019	National-level table tennis	8	14.5 ± 1.4	Male	166.7 ± 6.6 -0.6 ± 1.7 (PHV)	53.6 ± 7.9	Training volume Heart rate	Injury
Purnell et al., [173]	2010	Recreational and competitive acrobatic gymnasts	73	13.4 ± 3.6 20.5 ± 4.2	Both	-	-	Training volume	Injury
Raya-González et al., [174]	2019	Professional soccer	22	18.6 ± 0.6	Male	178.0 ± 4.0	72.2 ± 6.9	sRPE	Injury
Sugimoto et al., [176]	2019	Multi-sport athletes	236	15.3 ± 1.6 (single sport) 14.3 ± 1.7 (multi-sport)	Female	164.4 ± 8.4 (single sport) 163.0 ± 7.4 (multi-sport)	59.5 ± 12.0 (single sport) 55.5 ± 10 (mult-sport)	Volume	Injury

Visnes and Bahr, [178]	2013	High-school volleyball	141	16.8 ± 0.8	Both	187.0 ± 5.5 (healthy men) 186.0 ± 6.7 (injured men) 171.8 ± 6.5 (healthy women) 173.9 ± 6.7 (injured women)	75.3 ± 7.8 (healthy men) 76.3 ± 8.5 (injured men) 65.2 ± 7.5 (healthy women) 66.0 ± 13.0 (injured women)	Training volume	Injury
Von Rosen et al., [180]	2017	National orienteers	64	17.0	Both	-	-	Training volume	Injury
Von Rosen et al., [179]	2016	National orienteers	64	17.0 ± 1.0	Both	-	-	Training volume	Injury
Watson et al., [181]	2017	Soccer[a]	75	15.5 ± 1.6	Female	164.7 ± 6.6	57.3 ± 8.2	sRPE	Injury Illness
Antualpa et al., [130]	2018	State rhythmic gymnasts	23	12.1 ± 2.6	Female	143.9 ± 13.7	37.2 ± 9.4	sRPE	Illness
Brunelli et al., [136]	2012	Regional basketball	12	12.7 ± 0.6	Male	170.0 ± 10.0	57.6 ± 12.6	sRPE	Illness
Freitas et al., [144]	2014	Professional soccer	17	16.0 ± 0.5	Male	181.3 ± 5.8	75.2 ± 3.1	sRPE	Illness

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[b] = Range; [a] = no clear indication of level of athletes; NCAA D1 = National College Athletics Associations Division 1; ARF = Australian Rules Football; GNSS = Global national satellite systems; sRPE = session rating of perceived exertion; dRPE = differential rating of perceived exertion; APHV = Age of peak height velocity; PHV = peak height velocity; LPT = low plyometric training; HPT = high plyometric training; DC = Davis cup; RS = Regional squad; N = Newtons; M = Male; F = Female.

Table 4.4 presents the results of the best-evidence synthesis. There was moderate evidence of a relationship between resistance training volume load and strength. Additionally, there was moderate evidence of a relationship between throw count, and training duration and injury. Evidence for all other relationships were either limited or inconsistent.

Table 4.4. Best-evidence synthesis of relationship between monitoring tools and change in physical qualities, injury or illness.

		Physical qualities									
		Aerobic fitness	Strength	Speed	Power	Change of direction	Flexibility	Muscular endurance	Repeated sprint ability	Injury	Illness
External training loads											
GNSS	Total Distance	-		↑						?	
	High speed running (>5 m.s)	?								?	
	Player Load	-									
	Acceleration/Deceleration load			↑						?	
Accelerometer	Vertical ground reaction force									↑	
	Strides per session									-	
	Cumulative loading			-						↑	
Training duration		?	?	?	?	↑				↑↑	↑
Resistance training volume load			↑↑	?	↑						
Throw Count										↑↑	
Internal training loads											
Heart rate	iTRIMP	?									
	eTRIMP			↑						↑	
	bTRIMP	?									
	luTRIMP	?									
	TeamTRIMP	-									
sRPE		?		?	?	?	-	-	?	?	?
dRPE		↑		↓	↑						

↑↑↑ = Strong positive relationship; ↑↑ = Moderate positive relationship; ↑ = Limited positive relationship; ↓↓↓ = Strong negative relationship; ↓↓ = Moderate negative relationship; ↓ = limited negative relationship; ? = Inconsistent significant relationships; - = no significant relationship reported; iTRIMP = Individualised training impulse; eTRIMP = Edwards training impulse; bTRIMP = Bannisters training impulse; luTRIMP = Lucia's training impulse; TeamTRIMP = team training impulse; sRPE = session rating of perceived exertion; dRPE = differential ratings of perceived exertion; GNSS = Global navigation satellite system.

4.3.2 Relationship between external training loads and physical qualities

Table 4.5 presents the relationships between external training loads and physical qualities. Nineteen studies investigated the relationship between external training loads and physical qualities [31, 63, 64, 66, 67, 133, 138, 141, 145-147, 155, 167, 183], only one reported no significant relationships [138].

There was inconsistent or limited evidence of a relationship between GNSS metrics with change in physical qualities. Significant results were found for positive [66] and negative [67] relationships between high-speed running and changes in aerobic fitness, and a positive relationship for acceleration/deceleration and total distance with changes in sprint speed [66].

Training duration showed inconsistent evidence of a relationship with changes in physical qualities. Results for training duration were non-significant [145], negative [167], and positive [133] with aerobic fitness; non-significant [31] and negative [167] for power; non-significant [31] and negative [145] for speed; inconsistent for change of direction [167]; and non-significant [31] and positive [141] for strength.

Resistance training metrics showed inconsistent evidence of a relationship to changes in speed, but there was moderate evidence of relationship to changes in strength. Relationships between resistance training metrics and speed were non-significant [31, 138], or irregular [155]. Relationships to strength were positive between chin up 3 repetition maximum (RM) and upper body exercises, upper body volume (sets x reps x mass (kg)) and total (upper and lower body) volume [31], positive between bench press 3RM and upper body exercises and upper body volume [31], positive for snatch 1RM and total volume between medium and low volume groups [146], and positive for snatch and squat 1RM and number of lifts performed at 100% 1RM [147]. Relationships to power were observed to be non-significant for plyometrics volume measured via number of contacts [138], and positive for lower body exercises, lower body volume, and total volume [31]. Additionally, one study found upper body resistance training volume to be related to 800m time [152].

Table 4.5. Results of external methods of monitoring load and relationship with change in physical qualities

Monitoring method	Measure	Relationship	Reference
GNSS	Acceleration/Deceleration load vs. MAS	r = 0.20 (90%CI -0.29, 0.60)	[66]
	Acceleration/Deceleration load vs. Maximal Sprint Speed	r = 0.57 (90%CI 0.15, 0.81); $R^2 = 0.32$	[66]
	Distance > 15 km.h^{-1} vs. Velocity at lactate threshold	r = -0.06 (99%CI -0.77, 0.72); $p = 0.87$	[177]
	Distance > 15 km·h^{-1} vs. Velocity at $\dot{V}O_{2max}$	r = 0.32 (99%CI -0.57, 0.86); $p = 0.36$	[177]
	Distance > 15 km.h^{-1} vs. $\dot{V}O_{2max}$	r = -0.19 (99%CI -0.82, 0.65); $p = 0.59$	[177]
	Distance > 15 km.h^{-1} vs. vOBLA	r = 0.25 (99%CI -0.62, 0.87); $p = 0.49$	[177]
	Distance > 18km.h^{-1} vs. Velocity at $\dot{V}O_{2max}$	r = -0.16 (99%CI -0.81, 0.67); $p = 0.66$	[177]
	Distance > 18km.h^{-1} vs. vLT	r = -0.43 (99%CI -0.89, 0.22); $p = 0.22$	[177]
	Distance > 18km.h^{-1} vs. $\dot{V}O_{2max}$	r = -0.63 (99%CI -0.94, 0.23); $p = 0.05$	[177]
	Distance > 18km.h-1 vs. vOBLA	r = -0.66 (99%CI -0.94, 0.18); $p = 0.04$*	[177]
	Distance > 21km.h^{-1} vs. MAS	r = -0.70 (90%CI -0.51, 0.40); $R^2 = 0.00$	[66]
	Distance > 21km.h^{-}vs. Maximal Sprint Speed	r = 0.25 (90%CI -0.24, 0.64); $R^2 = 0.06$	[66]
	Distance > 25.2 km.h^{-1} vs. MAS	r = -0.10 [95%CI -0.74 to 0.54]; $R^2 = 0.12$ [95%CI 0.00, 0.39],	[182]
	Distance > 25.2 km.h^{-1} vs. Speed at 2 mmol.l	r = -0.22 [95%CI -0.80, 0.43]; $R^2 = 0.15$ [95%CI 0.00, 0.44]	[182]

Distance > 25.2 $km.h^{-1}$ vs. Speed at 4 mmol.l	r = -0.15 [95%CI -0.76, 0.49]; R^2 = 0.13 [95%CI 0.00 to 0.42]	[182]
Distance > 30% ASR vs. MAS	r = 0.20 (90%CI -0.28, 0.61); R^2 = 0.04	[66]
Distance > 30% ASR vs. Maximal Sprint Speed	r = -0.09 (90%CI -0.53, 0.39); R^2 = 0.01	[66]
Distance > MAS vs. MAS	r = 0.5 (90%CI -0.6, 0.78); R^2 = 0.25	[66]
Distance > MAS vs. Maximal Sprint Speed	r = 0.30 (90%CI -0.18, 0.67); R^2 = 0.25	[66]
Distance > speed at 4mmol.l vs. MAS	r = 0.27 [95%CI -0.37, 0.82]; R^2 = 0.16 [95%CI 0.00, 0.47]	[182]
Distance > speed at 4mmol.l vs. Speed at 2 mmol.l	r = -0.01 [95%CI -0.73, 0.56]; R^2 = 0.12 [95%CI 0.00, 0.40]	[182]
Distance > speed at 4mmol.l vs. Speed at 4 mmol.l	r = -0.12 [95%CI -0.71, 0.56]; R^2 = 0.12 [95%CI 0.00, 0.40]	[182]
Distance > vOBLA vs. Velocity at $\dot{V}O_{2max}$	r = 0.34 (99%CI -0.55, 0.87); p = 0.33	[177]
Distance > vOBLA vs. vLT	r = 0.12 (99%CI -0.70, 0.80); p = 0.75	[177]
Distance > vOBLA vs. $\dot{V}O_{2max}$	r = -0.26 (99%CI -0.85, 0.61); p = 0.47	[177]
Distance > vOBLA vs. vOBLA	r = 0.27 (99%CI -0.61, 0.85); p = 0.46	[177]
Distance between 14.4 and 19.8 $km.h^{-1}$ vs. MAS	r = 0.11 [95%CI -0.52, 0.73]; R^2 = 0.12 [95%CI 0.00, 0.39]	[182]
Distance between 14.4 and 19.8 $km.h^{-1}$ vs. Speed at 2 mmol.l	r = -0.45 [95%CI -0.90, 0.17]; R^2 = 0.27 [95%CI 0.00, 0.57]	[182]
Distance between 14.4 and 19.8 $km.h^{-1}$ vs. Speed at 4 mmol.l	r = -0.45 [95%CI -0.89, 0.19]; R^2 = 0.27 [95%CI 0.00, 0.56]	[182]
Distance between 19.8 and 25.2 $km.h^{-1}$ vs. MAS	r = -0.06 [95%CI -0.69, 0.58];	[182]

	$R^2 = 0.12$ [95%CI 0.00, 0.39]	
Distance between 19.8 and 25.2 km.h^{-1} vs. Speed at 2 mmol.l	r = -0.25 [95%CI -0.81, 0.41]; $R^2 = 0.18$ [95%CI 0.00, 0.49]	[182]
Distance between 19.8 and 25.2 km.h^{-1} vs. Speed at 4 mmol.l	r = -0.33 [95%CI -0.86, 0.32]; $R^2 = 0.22$ [95%CI 0.00, 0.54]	[182]
Distance vs. MAS	r = 0.34 [95%CI -0.30, 0.85]; $R^2 = 0.21$ [95%CI 0.00 to 0.51]	[182]
Distance vs. MAS	r = 0.26 (90%CI -0.23, 0.64)	[66]
Distance vs. Maximal Sprint Speed	r = 0.46 (90%CI 0.00, 0.76); $R^2 = 0.21$	[66]
Distance vs. Speed at 4 mmol.l	r = -0.11 [95%CI 0.74, 0.54]^z; $R^2 = 0.11$ [95%CI 0.00, 0.37]	[182]
Distance vs. Velocity at 2 mmol.l	r = -0.14 [95%CI -0.74, 0.51]; $R^2 = 0.12$ [95%CI 0.00, 0.40]	[182]
Distance vs. Velocity at $\dot{V}O_{2max}$	r = -0.002 (99%CI -0.75, 0.75); $p = 0.99$	[177]
Distance vs. vLT	r = -0.21 (99%CI -0.83, 0.64); $p = 0.56$	[177]
Distance vs. $\dot{V}O_{2max}$	r = -0.51 (99%CI -0.91, 0.39); $p = 0.13$	[177]
Distance vs. vOBLA	r = -0.31 (99%CI -0.86, 0.57); $p = 0.38$	[177]
Player load vs. MAS	r = 0.56 [95%CI -0.34, 0.94]; $R^2 = 0.38$ [95%CI 0.01, 0.63]	[182]
Player load vs. Speed at 2 mmol.l	r = 0.49 [95%CI -0.13, 0.90]; $R^2 = 0.30$ [95%CI 0.01, 0.58]	[182]
Player load vs. Speed at 4 mmol.l	r = 0.51 [95%CI -0.10, 0.92]; $R^2 = 0.31$ [95%CI 0.00, 0.59]	[182]
Player load vs. Velocity at $\dot{V}O_{2max}$	r = -0.17 (99%CI -0.67, 0.82); $p = 0.64$	[177]
Player load vs. vLT	r = -0.03 (99%CI -0.76, 0.74);	[177]

		$p = 0.93$	
	Player load vs. $\dot{V}O_{2max}$	r = -0.24 (99%CI -0.84, 0.62); $p = 0.5$	[177]
	Player load vs. vOBLA	r = -0.47 (99%CI -0.9, 0.43); $p = 0.17$	[177]
	Time > 17km.h^{-1} vs. MAS	r = 0.22 (90%CI -0.27, 0.62); $R^2 = 0.05$	[66]
	Time > 17km.h^{-1} vs. MAS	r = 0.37 (90%CI -0.17, 0.68); $R^2 = 0.14$	[66]
	Time > 17km.h^{-1} vs. Maximal Sprint Speed	r = 0.34 (90%CI -0.15, 0.69); $R^2 = 0.11$	[66]
	Time > 21km.h^{-1} vs. MAS	r = 0.05 (90%CI -0.42, 0.50); $R^2 = 0.14$	[66]
	Time > 21km.h^{-1} vs. Maximal Sprint Speed	r = 0.27 (90%CI -0.22, 0.65); $R^2 = 0.07$	[66]
	Time > 30% ASR vs. MAS	r = 0.62 (90%CI 0.22, 0.84); $R^2 = 0.38$	[66]
	Time > 30% ASR vs. Maximal Sprint Speed	r = -0.15 (90%CI -0.57, 0.33); $R^2 = 0.02$	[66]
	Time > MAS vs. MAS	r = 0.77 (90%CI 0.48, 0.91); $R^2 = 0.59$	[66]
	Time > MAS vs. Maximal Sprint Speed	r = 0.21 (90%CI -0.28, 0.61); $R^2 = 0.04$	[66]
Resistance training volume	High or low volume group vs. Snatch & Clean and Jerk in medium volume group	No significant difference reported	[146]
	High volume group vs. Snatch in medium volume group	p = 0.09	[146]
	Lower-body exercises vs. Squat (kg)	r = 0.30; $p > 0.05$	[31]
	Lower-body volume load vs. Squat (kg)	r = 0.30; $p > 0.05$	[31]
	Lower-body volume load vs. CMJ Height	r = 0.74; $p < 0.05$*	[31]

Lower-body volume load vs. CMJ mean force	$r = 0.49$; $p < 0.05$*	[31]
Lower-body volume load vs. 20m sprint	$r = 0.19$; $p > 0.05$	[31]
Lower-body volume load vs. 40m sprint	$r = 0.10$; $p > 0.05$	[31]
Medium volume group compared to low volume group vs. Snatch 1 RM	$p = 0.0015$*	[146]
Number of lifts performed at 100%1RM in the snatch in the medium intensity and high intensity groups vs. Snatch 1 RM	$r = 0.52$; $p = 0.015$*	[147]
Number of lifts performed at 100%1RM in the squat in the medium intensity and high intensity groups vs. Squat 1 RM	$r = 0.47$; $p = 0.03$*	[147]
Number of lifts performed at 90-100% 1RM in the Clean and Jerk in the medium intensity group and high intensity group vs. Clean and jerk 1 RM	$r = -0.47$; $p = 0.055$	[147]
Number of loaded jumps vs. 20m sprint	$r = -0.54$; $p < 0.05$*	[155]
Number of loaded jumps vs. Fly 10 (10-20m of 30m)	$r = -0.56$; $p < 0.05$*	[155]
Number of repetitions of squat vs. 10m sprint	$r = -0.56$ $p < 0.05$*	[155]
Number of repetitions of squat vs. 20m sprint	$r = 0.58^{z}$; $p < 0.05$*	[155]
Number of repetitions of squat vs. 30m sprint	$r = -0.56$; $p < 0.05$*	[155]
Number of repetitions of squat vs. Fly 10 (10-20 of 30m)	$r = -0.56$; $p < 0.05$*	[155]
Number of unloaded jumps vs. 20m sprint	$r = -0.53$; $p < 0.05$*	[155]
Number of unloaded jumps vs. 30m sprint	$r = -0.53$; $p < 0.05$*	[155]
Number of unloaded jumps vs. Fly 10 (10-20 of 30m)	$r = - 0.56$; $p < 0.05$*	[155]
Plyometric volume vs. CMJ	$ES = 0.00$; $p = 0.95$	[138]
Plyometric volume vs. Squat jump	$ES = 0.00$; $p = 0.96$	[138]
Plyometric volume vs. Standing long jump	$ES = 0.00$; $p = 0.96$	[138]
Plyometric volume vs. T-Test	$ES = 0.39$; $p = 0.18$	[138]
Volume load vs. Bench Press (kg)	$r = 0.31$; $p > 0.05$	[31]

	Volume load vs. Chin up (kg)	$r = 0.72$; $p < 0.01$*	[31]
	Volume load vs. Squat (kg)	$r = 0.25$; $p > 0.05$	[31]
	Upper-body exercises vs. Bench Press (kg)	$r = 0.41$; $p \leq 0.05$*	[31]
	Upper-body exercises vs. Chin up (kg)	$r = 0.65$; $p < 0.01$*	[31]
	Upper-Body volume load vs. Bench Press (kg)	$r = 0.45$; $p < 0.01$*	[31]
	Upper-Body volume load vs. Chin up (kg)	$r = 0.73$; $p < 0.01$*	[31]
	Upper body volume load vs. 800m time	$r = 0.778$, $p = 0.04$*	[152]
Volume (Time)	Minutes training vs. time to exhaustion	$r = 0.67$ (90%CI ± 0.21)	[145]
	Minutes spent resistance training vs. 20m Sprint (%)	$r = 0.26$; $P > 0.05$	[31]
	Minutes spent resistance training vs. 40m Sprint (%)	$r = 0.04$; $P > 0.05$	[31]
	Minutes spent resistance training vs. Bench Press 3RM (kg)	$r = 0.19$; $p > 0.05$	[31]
	Minutes spent resistance training vs. Chin up 3RM (kg)	$r = 0.33$; $p > 0.05$	[31]
	Minutes spent resistance training vs. CMJ height (%)	$r = 0.18$; $P > 0.05$	[31]
	Minutes spent resistance training vs. CMJ Mean force (%)	$r = 0.16$; $P > 0.05$	[31]
	Minutes spent resistance training vs. Squat 3RM (kg)	$r = 0.24$; $p > 0.05$	[31]
	Minutes training (Under 15) vs. 15m sprint	$r = 0.63 \pm 0.45$	[167]
	Minutes training (Under 15) vs. 5m sprint	$r = 0.72 \pm 0.38$	[167]
	Minutes training (Under 15) vs. CMJ Height	$r = -0.70 \pm 0.40$	[167]
	Minutes training (Under 15) vs. T-Test	$r = 0.61 \pm 0.46$	[167]
	Minutes training (Under 15) vs. YoYoIR1	$r = -0.74 \pm 0.36$	[167]
	Minutes training (Under 16) vs. 15m sprint	$r = 0.54 \pm 0.43$	[167]
	Minutes training (Under 16) vs. 5m sprint	$r = 0.52 \pm 0.44$	[167]
	Minutes training (Under 16) vs. CMJ Height	$r = 0.39 \pm 0.49$	[167]

Minutes training (Under 16) vs. T-Test	r = 0.31 ± 0.51	[167]
Minutes training (Under 16) vs. YoYoIR1	r = -0.03 ± 0.52	[167]
Hours spent physical training vs. Grip Strength	R = 0.64; p = 0.03*	[141]
Hours training vs. HR in submax shuttle run	1 hr of training = -0.9 beats.min change	[133]

*Statistically significant result; ^{Z}Inconsistent or erroneous datum. HSR = High Speed Running; IHSR = Individualized High speed running; VHSR = Very high speed running; CMJ = Countermovement Jump; MAS = Maximal aerobic speed; ASR = Anaerobic Speed Reserve; RM = repetition maximum; bTRIMP = Banisters training impulse; eTRIMP = Edwards training impulse; iTRIMP = Individualised training impulse; luTRIMP = Lucia's training impulse; Yo-Yo IR1 = Yo-Yo Intermittent recovery test level 1; vOBLA = velocity at onset of blood lactate accumulation; vLT = velocity at lactate threshold.

4.3.3 Relationship between external training loads and injury

The relationships between external training load and injury are shown in Table 4.6. There was inconsistent or limited evidence of a relationship between external training loads and injury. 22 studies found significant relationships [67, 129, 131-133, 143, 148, 150, 151, 153, 156, 157, 159, 168-173, 178-180], whilst three had non-significant findings [137, 149, 176]. Of the studies that found significant results, one found greater training load to decrease the risk of injury in at least one variable [129]. The remaining 21 studies found greater training load, in at least one variable, was associated with increased injury risk [67, 131-133, 148, 153, 157, 159, 169, 170, 172, 173, 178-180]. However, when pooled, less than 50% of contributing findings were significant.

For GNSS and injury risk positive relationships with high and very high accelerations [132], and both positive [132] and negative [131] relationships with total distance were reported.

There was moderate evidence of a relationship between training duration and injury risk, with, non-significant [137, 149, 176], negative [129], and positive relationships [67, 133, 148, 150, 151, 157, 159, 169-171, 173, 176, 178-180] reported. Furthermore, 56% of contributing findings indicated a positive relationship.

Table 4.6. Results of external methods of monitoring training load and relationship with injury

Monitoring method	Measure vs. Injury risk	Relationship	Reference
Accelerometer	Mean estimated peak vGRF	$p = 0.01$*	[153]
	Mean number of strides per training session	$p = 0.091$	[153]
	Mean weighted cumulative loading per session	$p < 0.01$*	[153]
GNSS	2 week cumulative HSR distance 1 standard deviation above mean	OR = 0.580 [95%CI 0.330 - 1.021]; $p = 0.059$	[131]
	2 week cumulative HSR distance 1 standard deviation below mean	OR = 0.993 [95%CI 0.381 - 2.588]; $p = 0.989$	[131]
	2 week cumulative total distance 1 standard deviation above mean	OR = 0.670 [95%CI 0.395 - 1.137]; $p = 0.137$	[131]
	2 week cumulative total distance 1 standard deviation below mean	OR = 1.264 [95%CI 0.164 - 9.769]; $p = 0.822$	[131]
	3 week cumulative HSR distance 1 standard deviation above mean	OR = 1.049 [95%CI 0.543 - 2.029]; $p = 0.886$	[131]
	3 week cumulative HSR distance 1 standard deviation below mean	OR = 0.506 [95%CI 0.212 - 1.206]; $p = 0.124$	[131]
	3 week cumulative total distance 1 standard deviation above mean	OR = 0.953 [95%CI 0.442 - 2.054]; $p = 0.903$	[131]
	3 week cumulative total distance 1 standard deviation below mean	OR = 0.688 [95%CI 0.290 - 1.635]; $p = 0.397$	[131]
	4 week cumulative HSR distance 1 standard deviation above mean	OR = 1.049 [95%CI 0.543 - 2.029]; $p = 0.886$	[131]
	4 week cumulative HSR distance 1 standard deviation below mean	OR = 0.506 [95%CI 0.212 - 1.206]; $p = 0.124$	[131]
	4 week cumulative total distance 1 standard deviation above mean	OR = 0.953 [95%CI 0.442 - 2.054]; $p = 0.903$	[131]
	4 week cumulative total distance 1 standard deviation below mean	OR = 0.688 [95%CI 0.290 - 1.635]; $p = 0.397$	[131]

High 1 week accelerations	RR = 1.83; $p < 0.05$*	[132]
High 1 week distance > $20km.h^{-1}$	RR = 0.59; $p > 0.05$	[132]
High 1 week total distance	RR = 1.57; $p > 0.05$	[132]
High 2 week accelerations	RR = 1.37; $p > 0.05$	[132]
High 2 week distance > $20km.h^{-1}$	RR = 1.45; $p > 0.05$	[132]
High 2 week total distance	RR = 1.27; $p > 0.05$	[132]
High 3 week accelerations	RR = 1.38; $p > 0.05$	[132]
High 3 week distance > $20km.h^{-1}$	RR = 1.66; $p < 0.05$*	[132]
High 3 week total distance	RR = 1.31; $p > 0.05$	[132]
High 4 week accelerations	RR = 1.66; $p < 0.05$*	[132]
High 4 week accelerations ACWR	RR = 1.44; $p > 0.05$	[132]
High 4 week accelerations ACWR with high chronic workload	RR = 1.1; $p > 0.05$	[132]
High 4 week accelerations ACWR with low chronic workload	RR = 1.7; $p > 0.05$	[132]
High 4 week distance > $20km.h^{-1}$	RR = 1.26; $p > 0.05$	[132]
High 4 week distance > $20km.h^{-1}$ACWR	RR = 0.98; $p > 0.05$	[132]
High 4 week distance > $20km.h^{-1}$ACWR with high chronic workload	RR = 0.50; $p > 0.05$	[132]
High 4 week distance > $20km.h^{-1}$ACWR with low chronic workload	RR = 1.82; $p > 0.05$	[132]
High 4 week total distance	RR = 1.64; $p < 0.05$*	[132]
High 4 week total distance ACWR	RR = 1.13; $p > 0.05$	[132]
High 4 week total distance ACWR with high chronic workload	RR = 1.21; $p > 0.05$	[132]
High 4 week total distance ACWR with low chronic workload	RR = 1.76; $p > 0.05$	[132]
HSR	$R^2 = 0.025$; $p = 0.323$	[131]
Low 1 week accelerations	RR = 0.35; $p < 0.05$	[132]

Low 1 week distance > 20km.h^{-1}	RR = 0.38; $p < 0.05$*	[132]
Low 1 week total distance	RR = 0.25; $p < 0.001$*	[132]
Low 2 week accelerations	RR = 0.51; $p > 0.05$	[132]
Low 2 week distance > 20km.h^{-1}	RR = 0.30; $p < 0.05$*	[132]
Low 2 week total distance	RR = 0.62; $p > 0.05$	[132]
Low 3 week accelerations	RR = 0.63; $p > 0.05$	[132]
Low 3 week distance > 20km.h^{-1}	RR = 0.67; $p > 0.05$	[132]
Low 3 week total distance	RR = 0.53; $p > 0.05$	[132]
Low 4 week accelerations	RR = 0.93; $p > 0.05$	[132]
Low 4 week accelerations ACWR	RR = 0.85; $p > 0.05$	[132]
Low 4 week accelerations ACWR with high chronic workload	RR = 0.71; $p > 0.05$	[132]
Low 4 week accelerations ACWR with low chronic workload	RR = 0.29; $p < 0.05$*	[132]
Low 4 week distance > 20km.h^{-1}	RR = 0.79; $p > 0.05$	[132]
Low 4 week distance > 20km.h^{-1}ACWR	RR = 0.47; $p < 0.05$*	[132]
Low 4 week distance > 20km.h^{-1}ACWR with high chronic workload	RR = 1.52; $p > 0.05$	[132]
Low 4 week distance > 20km.h^{-1}ACWR with low chronic workload	RR = 0.47; $p > 0.05$	[132]
Low 4 week total distance	RR = 0.89; $p > 0.05$	[132]
Low 4 week total distance ACWR	RR = 1; $p > 0.05$	[132]
Low 4 week total distance ACWR with high chronic workload	RR = 0.91; $p > 0.05$	[132]
Low 4 week total distance ACWR with low chronic workload	RR = 0.28; $p < 0.05$*	[132]
Moderate-high 1 week accelerations	RR = 1; $p > 0.05$	[132]
Moderate-high 1 week distance > 20km.h^{-1}	RR = 1.73; $p < 0.05$*	[132]
Moderate-high 1 week total distance	RR = 0.95; $p > 0.05$	[132]

Moderate-high 2 week accelerations	RR = 1.21; $p > 0.05$	[132]
Moderate-high 2 week distance > $20km.h^{-1}$	RR = 1.72; $p < 0.05$*	[132]
Moderate-high 2 week total distance	RR = 1.55; $p < 0.05$*	[132]
Moderate-high 3 week accelerations	RR = 1.32; $p > 0.05$	[132]
Moderate-high 3 week distance > $20km.h^{-1}$	RR = 1.15; $p > 0.05$	[132]
Moderate-high 3 week total distance	RR = 1.36; $p > 0.05$	[132]
Moderate-high 4 week accelerations	RR = 1.01; $p > 0.05$	[132]
Moderate-high 4 week accelerations ACWR	RR = 1.15; $p > 0.05$	[132]
Moderate-high 4 week accelerations ACWR with high chronic workload	RR = 1.25; $p > 0.05$	[132]
Moderate-high 4 week accelerations ACWR with low chronic workload	RR = 0.94; $p > 0.05$	[132]
Moderate-high 4 week distance > $20km.h^{-1}$	RR = 1.56; $p < 0.05$*	[132]
Moderate-high 4 week distance > $20km.h^{-1}$ACWR	RR = 1.32; $p > 0.05$	[132]
Moderate-high 4 week distance > $20km.h^{-1}$ACWR with high chronic workload	RR = 1.27; $p > 0.05$	[132]
Moderate-high 4 week distance > $20km.h^{-1}$ACWR with low chronic workload	RR = 1.3; $p > 0.05$	[132]
Moderate-high 4 week total distance	RR = 1.19; $p > 0.05$	[132]
Moderate-high 4 week total distance ACWR	RR = 0.97; $p > 0.05$	[132]
Moderate-high 4 week total distance ACWR with high chronic workload	RR = 1.19; $p > 0.05$	[132]
Moderate-high 4 week total distance ACWR with low chronic workload	RR = 0.97; $p > 0.05$	[132]
Moderate-low 1 week accelerations	RR = 1.01; $p > 0.05$	[132]
Moderate-low 1 week distance > $20km.h^{-1}$	RR = 1.16; $p > 0.05$	[132]
Moderate-low 1 week total distance	RR = 1.38; $p > 0.05$	[132]
Moderate-low 2 week accelerations	RR = 0.92; $p > 0.05$	[132]

Moderate-low 2 week distance > 20km.h^{-1}	RR = 0.81; $p > 0.05$	[132]
Moderate-low 2 week total distance	RR = 0.76; $p > 0.05$	[132]
Moderate-low 3 week accelerations	RR = 0.77; $p > 0.05$	[132]
Moderate-low 3 week distance > 20km.h^{-1}	RR = 0.84; $p > 0.05$	[132]
Moderate-low 3 week total distance	RR = 1.23; $p > 0.05$	[132]
Moderate-low 4 week accelerations	RR = 0.82; $p > 0.05$	[132]
Moderate-low 4 week accelerations ACWR	RR = 1.16; $p > 0.05$	[132]
Moderate-low 4 week accelerations ACWR with high chronic workload	RR = 1.04; $p > 0.05$	[132]
Moderate-low 4 week accelerations ACWR with low chronic workload	RR = 1.49; $p > 0.05$	[132]
Moderate-low 4 week distance > 20km.h^{-1}	RR = 0.73; $p > 0.05$	[132]
Moderate-low 4 week distance > 20km.h^{-1}ACWR	RR = 1.10; $p > 0.05$	[132]
Moderate-low 4 week HSR distance ACWR with high chronic workload	RR = 1.11; $p > 0.05$	[132]
Moderate-low 4 week HSR distance ACWR with low chronic workload	RR = 0.86; $p > 0.05$	[132]
Moderate-low 4 week total distance	RR = 0.73; $p > 0.05$	[132]
Moderate-low 4 week total distance ACWR	RR = 1.25; $p > 0.05$	[132]
Moderate-low 4 week total distance ACWR with high chronic workload	RR = 0.98; $p > 0.05$	[132]
Moderate-low 4 week total distance ACWR with low chronic workload	RR = 1.43; $p > 0.05$	[132]
Total distance	$R^2 = 0.14$; $p = 0.015$	[131]
Very high 1 week accelerations	RR = 3.06; $p < 0.05$*	[132]
Very high 1 week distance > 20km.h^{-1}	RR = 0.82; $p > 0.05$	[132]
Very high 1 week total distance	RR = 2.59; $p > 0.05$	[132]
Very high 2 week accelerations	RR = 3.19; $p < 0.05$*	[132]
Very high 2 week distance > 20km.h^{-1}	RR = 0.00; $p > 0.05$	[132]

	Very high 2 week total distance	RR = 2.88; $p > 0.05$	[132]
	Very high 3 week accelerations	RR = 3.84; $p < 0.05$*	[132]
	Very high 3 week distance > 20km.h^{-1}	RR = 0.33; $p > 0.05$	[132]
	Very high 3 week total distance	RR = 2.37; $p > 0.05$	[132]
	Very high 4 week accelerations	RR = 2.37; $p > 0.05$	[132]
	Very high 4 week accelerations ACWR	RR = 2.09; $p > 0.05$	[132]
	Very high 4 week accelerations ACWR with high chronic workload	RR = 2.71; $p > 0.05$	[132]
	Very high 4 week distance > 20km.h^{-1}	RR = 0.33; $p > 0.05$	[132]
	Very high 4 week distance > 20km.h^{-1} ACWR	RR = 0.95; $p > 0.05$	[132]
	Very high 4 week distance > 20km.h^{-1}ACWR with high chronic workload	RR = 1.63; $p > 0.05$	[132]
	Very high 4 week total distance	RR = 1.29; $p > 0.05$	[132]
	Very high 4 week total distance ACWR	RR = 2.09; $p > 0.05$	[132]
	Very high 4 week total distance ACWR with high chronic workload	RR = 1.8; $p > 0.05$	[132]
	Very high 4 week total distance ACWR with low chronic workload	RR = --	[132]
Throw Count	28 day rolling average	$p = 0.014$	[158]
	>100 pitches per year	OR = 3.50 (95%CI 1.16 – 10.44); $p = 0.049$*	[143]
	Game pitch count 25 – 49 vs. elbow injury	OR = 1.03; $p = 0.07$	[156]
	Game pitch count 50 – 74 vs. elbow injury	OR = 1.21; $p = 0.07$	[156]
	Game pitch count 75 – 99 vs. elbow injury	OR = 1.35; $p = 0.07$	[156]
	Game pitch count 100+ vs. elbow injury	OR = 1.44; $p = 0.07$	[156]
	Game pitch count 25 – 49 vs. shoulder injury	OR = 1.15; $p = 0.01$*	[156]
	Game pitch count 50 – 74 vs. shoulder injury	OR = 1.23; $p = 0.01$*	[156]
	Game pitch count 75 – 99 vs. shoulder injury	OR = 1.52; $p = 0.01$*	[156]

Volume (Time)	Game pitch count 100+ vs. shoulder injury	OR = 1.77; p = 0.01*	[156]
	>60% increase in training hours compared to 20% increase	HRR = 1.91 [1.00 - 3.70]; p = 0.05*	[159]
	2 week training time	OR = 0.98 [95%CI 0.95 - 1.01]; p = 0.04*	[129]
	2 week training time ACWR	OR = 0.87 [95%CI 0.58 - 1.30]; p = 0.91	[129]
	20-60% increase in training hours compared 20% increase	HRR = 1.22 [0.62 - 2.40]; p = 0.57	[159]
	3 week training time	OR = 0.97 [95%CI 0.94 - 1.00]; p = 0.02*	[129]
	3 week training time ACWR	OR = 0.93 [95%CI 0.67 - 1.29]; p = 1	[129]
	4 week training time	OR = 0.97 [95%CI 0.93 - 1.00]; p = 0.02*	[129]
	4 week training time ACWR	OR = 0.90 [95%CI 0.66 - 1.23]; p = 0.57	[129]
	Beach volleyball training time	p = 0.8	[178]
	Competition time	β = -0.701; p = 0.009*	[179]
	Competition time	OR = 1.41 [95%CI 1.14 – 1.74]; p = 0.001*	[148]
	Competition time per week	d = 0.47; p = 0.001*	[170]
	Fitness training time ACWR > 1.3 vs. back injury	HRR = 1.13 [95% 1.05 – 1.22] p = 0.15	[150]
	Fitness training time ACWR > 1.3 vs. shoulder injury	HRR = 1.18 [95%CI 1.09 – 1.27]	[151]
	High competition time vs. Lower extremity risk	OR = 2.08 [95%CI 1.55 - 2.80]; p = 0.001*	[169]
	Hours playing sport	p < 0.001*	[170]
	Hours playing sports exceeding age	p = 0.002*	[170]
	Hours training vs. Lower extremity overuse injury	OR = 1.10 [95%1.01 - 1.18]; p = 0.34	[176]
	Increased days of competition	HRR = 1.24 [95%CI 0.91 - 1.69]; p = 0.172	[180]
	Increased hours of training	HRR = 1.40 [95%CI 1.07 - 1.82]; p = 0.015*	[180]
	Individual running exposure	r = 0.83; R^2 = 0.69*	[157]

Individual running exposure vs. Time loss overuse injury risk	r = 0.61*	[157]
Jump training	p = 0.04*	[178]
Moderate competition volume vs. Lower extremity injury risk	OR = 1.68 [95%CI 1.31, 2.16]; *p* <0.001*	[169]
Number of sets played	OR = 3.88 (95%CI 1.80 - 8.40); *p* = 0.001*	[178]
Other training	p = 0.26	[178]
Strength training time	p = 0.7	[178]
Tennis training time ACWR > 1.3 vs. back injury	HRR = 1.17 [95% 1.06 – 1.28] *p* = 0.08	[150]
Tennis training time ACWR > 1.3 vs. shoulder injury	HRR = 1.26 [95% 1.15 – 1.39]	[151]
Total training time ACWR > 1.3 vs. back injury	HRR = 1.18 [95% 1.07 – 1.30] *p* = 0.04*	[150]
Total training time ACWR > 1.3 vs. shoulder injury	HRR = 1.22 [95% CI 1.12 – 1.34]	[151]
Training hours per week at 11 years old	8 hours; AUC = 0.91; *p* = 0.002*	[173]
Training hours per week at 12 years old	8.5 hours; AUC = 0.79; *p* = 0.037*	[173]
Training hours per week at 13 years old	8.5 hours; AUC = 0.78; *p* = 0.049*	[173]
Training hours per week at 14 years old	9.75 hours; AUC = 0.72; *p* = 0.083	[173]
Training hours per week at 15 years old	12.75 hours; AUC = 0.75; *p* = 0.067	[173]
Training time	OR = 1.61 (95%CI 1.10 - 2.36); *p* = 0.02*	[178]
Training time	*p = 0.539*	[149]
Training time	OR = 1.03 [95%CI 0.78, 1.33]; *p* = 0.84	[148]
Training time	β = 0.184; *p* = 0.001*	[179]
Training time	d = 0.02; *p* = 0.842	[170]
Training time 1 week prior	OR = 1.02 [95%CI 0.98 - 1.05]; *p* = 0.33	[137]
Training time 2 weeks prior	OR = 0.98 [95%CI 0.94 - 1.01]; *p* = 0.20	[137]

Volleyball training time	OR = 1.72 (95%CI 1.18 - 2.53); $p = 0.005$*	[178]
Weekly training time	OR = 0.97 [95%CI 0.95 - 1.01]; $p = 0.09$	[129]
Weekly training time	R = 0.277; [95%CI 0.096 – 0.409]; $p = 0.001$*	[171]
Weekly training time	d = 0.19; $p = 0.387$	[170]
Weekly training time	OR = 1.19 [95%CI 0.93 – 1.51]; $p = 0.17$	[148]
Weekly training time vs. Overuse injury	OR = 1.07 (95%CI 0.98 - 1.18); $p \geq 0.05$	[134]
Weekly training time vs. Traumatic injury	OR = 1.14 (95%CI 1.06 - 1.23); $p < 0.05$*	[134]

*Statistically significant result; HSR = High Speed Running; ACWR = acute to chronic work to rest ratio; OR = Odds ratio; RR = Relative risk; HRR = Hazard risk ratio; vGRF = vertical ground reaction force.

4.3.4 External training loads and illness

The only study investigating the relationship between external training load and illness found the total duration of training and matches over a week was related to increased risk of illness that caused the withdrawal of an athlete from either training or competition (OR = 1.12 (95%CI 1.00 – 1.26); $p < 0.05$) [134].

4.3.5 Internal training load and physical qualities

Table 4.7 presents the relationships between internal training loads and physical qualities. Sixteen studies investigated the relationship between internal training loads and change in physical qualities [63-67, 135, 140, 142, 145, 161, 162, 164, 165, 167, 175, 184]. Of these studies, six found no significant relationships [63, 64, 66, 165, 175].

Heart rate metrics had inconsistent or limited evidence of a relationship to changes in physical qualities. Positive relationships to aerobic fitness were observed for individualised training impulse (iTRIMP), [64, 67], while Banisters training impulse (bTRIMP), Lucia's training impulse (LuTRIMP), and Edwards training impulse (eTRIMP) all had both non-significant and positive relationships observed [63-67]. Maximal sprint speed was also found to have a positive relationship with eTRIMP [67], although the strength of the evidence was limited.

The evidence of a relationship between sRPE and physical qualities was inconsistent or limited. There were non-significant [63, 64, 140, 177], positive [65, 135] and negative [142, 161, 167] findings for aerobic fitness; negative [161, 162, 167] and positive [140] findings for speed; negative [140, 167] and non-significant [161] findings for change of direction ability; non-significant findings for flexibility [184]; negative findings for muscular endurance [184]; and non-significant [135, 164, 165] findings for repeated sprint ability.

Studies investigating differential ratings of perceived exertion (dRPE) were limited, with various methods of quantifying load and inconsistent results. A positive relationship was seen between dRPE and aerobic fitness, but there were non-significant findings for speed and power [145]. Relationships between aerobic conditioning training load and physical qualities were negative for speed [140], and non-significant for power, change of direction or aerobic fitness [140]. Tactical, or skill-based, training load showed both non-significant [140] and negative [161, 162] relationships with aerobic fitness and negative relationships with repeated sprint ability [161]. A positive relationship was observed between strength and conditioning load, determined by the sRPE from all off court training including resistance and metabolic conditioning, and repeated sprint ability, but there were non-significant results for speed, change of direction, aerobic fitness and power [161]. Resistance training load showed positive relationships with speed, change of direction, and power [140].

Table 4.7. Results of relationship between internal training load and change in physical qualities

Monitoring method	Measure	Relationship	Reference
dRPE	sRPEmus Training load vs. 15m	$r = -0.15$ (90%CL +- 0.39)	[145]
	sRPEmus Training load vs. 5m sprint	$r = -0.06$ (90%CL +- 0.40)	[145]
	sRPEmus Training load vs. CMJ	$r = -0.17$ (90%CL +- 0.37)	[145]
	sRPEmus Training load vs. CMJA	$r = 0.17$ (90%CL +- 0.37)	[145]
	sRPEmus Training load vs. University of Montreal track test	$r = 0.69$ (90%CL +- 0.20)	[145]
	sRPEres Training load vs. 15m Sprint	$r = -0.21$ (90%CL +- 0.39)	[145]
	sRPEres Training load vs. 5m sprint	$r = -0.02$ (90%CL +- 0.41)	[145]
	sRPEres Training load vs. CMJ	$r = -0.06$ (90%CL +- 0.38)	[145]
	sRPEres Training load vs. University of Montreal track test	$r = 0.71$ (90%CL +- 0.19)	[145]
	sRPEres Training load vs. CMJA	$r = 0.25$ (90%CL +- 0.36)	[145]
Heart rate	bTRIMP vs. Heart rate at 2mmol.l - L	$r = 0.21$; $p > 0.05$	[177]
	bTRIMP vs. Heart rate at 4mmol.l - L	$r = -0.21$; $p > 0.05$	[177]
	bTRIMP vs. MAS	$r = 0.03$ [95%CI -0.59, 0.66]; $R^2 = 0.11$ [95%CI 0.00, 0.38]	[182]
	bTRIMP vs. Velocity at 2 mmol.l	$r = 0.33$ [95%CI -0.33, 0.87]; $R^2 = 0.23$ [95%CI 0.00, 0.54]	[182]
	bTRIMP vs. Velocity at 2mmol.l	R^2 (Quadratic) = 0.31 [99%CI -0.21, 0.83]; $p = 0.26$	[63]
	bTRIMP vs. Velocity at 2mmol.l	$r = 0.28$; $p > 0.05$	[177]
	bTRIMP vs. Velocity at 4 mmol.l	$r = 0.18$ [95%CI -0.48, 0.81]; $R^2 = 0.16$ [95%CI 0.00, 0.46]	[182]
	bTRIMP vs. Velocity at 4mmol.l	R^2 (Quadratic) = 0.21 [99%CI -0.28, 0.70]; $p = 0.43$	[63]
	bTRIMP vs. Velocity at 4mmol.l	$r = 0.43$; $p > 0.05$	[177]
	bTRIMP vs. Velocity at $\dot{V}O_{2max}$	R^2 (Quadratic) = 0.26 [99%CI -0.21, 0.57]; $p = 0.34$,	[63]
	bTRIMP vs. $\dot{V}O_{2max}$	R^2 (Quadratic) = 0.78 [99%CI 0.54, 1.00]; $p = 0.005$*	[63]

eTRIMP vs. MAS	r = 0.09 [95%CI -0.57, 0.69]; R^2 = 0.11 [95%CI 0.00, 0.38]	[182]
eTRIMP vs. MAS	r = -0.21 (90%CI -0.61, 0.28)	[66]
eTRIMP vs. Velocity at 2 mmol.l	r = 0.17 [95%CI -0.49, 0.77]; R^2 = 0.13 [95%CI 0.00, 0.42]	[182]
eTRIMP vs. Velocity at 2mmol.l	R^2 (Quadratic) = 0.11 [99%CI -0.29, 0.51]; *p* = 0.65	[63]
eTRIMP vs. Velocity at 4 mmol.l	r = 0.00 [95%CI -0.65, 0.67]; R^2 = 0.10 [95%CI 0.00, 0.35]	[182]
eTRIMP vs. Velocity at 4mmol.l	R^2 (Quadratic) = 0.27 [99%CI -0.25, 0.79]; *p* = 0.34	[63]
eTRIMP vs. Velocity at $\dot{V}O_{2max}$	R^2 (Quadratic) = 0.02 [99%CI -0.15, 0.19]; *p* = 0.93	[63]
eTRIMP vs. $\dot{V}O_{2max}$	R^2 (Quadratic) = 0.40 [99%CI -0.07, 0.87]; *p* = 0.17	[63]
eTRIMP vs. Yo-yo IR1	r = -0.51	[65]
iTRIMP vs. Heart rate at 2mmol.l - L	r = 0.17; $p > 0.05$	[177]
iTRIMP vs. Heart rate at 4mmol.l - L	r = -0.25; $p > 0.05$	[177]
iTRIMP vs. MAS	r = 0.37 [95%CI -0.28, 0.87]; R^2 = 0.22 [95%CI 0.00, 0.52]	[182]
iTRIMP vs. Velocity at 2 mmol.l	R^2 (Quadratic) = 0.22 [99%CI -0.29, 0.72]; *p* = 0.41	[63]
iTRIMP vs. Velocity at 2 mmol.l	r = 0.93 [95%CI 0.74, 1]; R^2 = 0.90 [95%CI 0.76, 0.93]*	[182]
iTRIMP vs. Velocity at 2 mmol.l	r = 0.67 (95%CI 0.01, 0.92); $p < 0.05$*	[177]
iTRIMP vs. Velocity at 4 mmol.l	R^2 (Quadratic) = 0.04 [99%CI -0.20, 0.28]; *p* = 0.93	[63]
iTRIMP vs. Velocity at 4 mmol.l	r = 0.88 [95%CI 0.62, 0.99] ; R^2 = 0.82 [95%CI 0.51, 0.88]*	[182]
iTRIMP vs. Velocity at 4mmol.l	r = 0.33; $p > 0.05$	[177]
iTRIMP vs. Velocity at $\dot{V}O_{2max}$	R^2 (Quadratic) = 0.15 [99%CI -0.26, 0.56] ; *p* = 0.56	[63]
iTRIMP vs. $\dot{V}O_{2max}$	R^2 (Quadratic) = 0.55 [99%CI 0.09, 1.00]; *p* = 0.06	[63]

	luTRIMP vs. MAS	r = 0.26 [95%CI -0.41, 0.83]; $R^2 = 0.16$ [95%CI 0.00, 0.47]	[182]
	luTRIMP vs. Velocity at 2 mmol.l	R^2 (Quadratic) = 0.20 [99%CI -0.29, 0.53]; $p = 0.46$	[63]
	luTRIMP vs. Velocity at 2 mmol.l	r = 0.75 [95%CI 0.26, 0.98]; $R^2 = 0.60$ [95%CI 0.12, 0.75]*	[182]
	luTRIMP vs. Velocity at 4 mmol.l	R^2 (Quadratic) = 0.02 [99%CI -0.16, 0.21]; $p = 0.93$	[63]
	luTRIMP vs. Velocity at 4 mmol.l	r = 0.82 [95%CI 0.44, 0.99]; $R^2 = 0.69$ [95%CI 0.20, 0.81]*	[182]
	luTRIMP vs. Velocity at $\dot{V}O_{2max}$	R^2 (Quadratic) = 0.49 [99%CI 0.05, 0.93]; $p = 0.1$	[63]
	luTRIMP vs. $\dot{V}O_{2max}$	R^2 (Quadratic) = 0.30 [99%CI -0.17, 0.77]; $p = 0.29$	[63]
	Team TRIMP vs. Heart rate at 2mmol.l - L	r = 0.28; $p > 0.05$	[177]
	Team TRIMP vs. Heart rate at 4mmol.l - L	r = -0.49; $p > 0.05$	[177]
	Team TRIMP vs. Velocity at 2mmol.l - L	r = 0.20; $p > 0.05$	[177]
	Team TRIMP vs. Velocity at 4mmol.l - L	r = 0.28; $p > 0.05$	[177]
sRPE	1 week training load vs. Anaerobic sprint rest average power	r = -0.04; $p > 0.05$	[164]
	1 week training load vs. Anaerobic sprint test fatigue index	r = 0.32; $p > 0.05$	[164]
	1 week training load vs. Anaerobic sprint test minimum power	r = 0.11; $p > 0.05$	[164]
	1 week training load vs. Anaerobic sprint test peak power	r = -0.08; $p > 0.05$	[164]
	1 week training load vs. Change of direction	r = 0.38; $p > 0.05$	[164]
	1 week training load vs. Yo-yo IR1	r = -0.07	[65]
	4 week ACWR vs. Anaerobic sprint rest average power	r = 0.13; $p > 0.05$	[164]
	4 week ACWR vs. Anaerobic sprint test fatigue index	r = 0.04; $p > 0.05$	[164]
	4 week ACWR vs. Anaerobic sprint test minimum power	r = -0.05; $p > 0.05$	[164]
	4 week ACWR vs. Anaerobic sprint test peak power	r = 0.08; $p > 0.05$	[164]
	4 week ACWR vs. Change of direction	r = 0.45; $p < 0.05$*	[164]
	Chronic Workload vs. Anaerobic sprint rest average power	r = 0.09; $p > 0.05$	[164]
	Chronic Workload vs. Anaerobic sprint test fatigue index	r = -0.22; $p > 0.05$	[164]

Chronic Workload vs. Anaerobic sprint test minimum power	$r = -0.01$; $p > 0.05$	[164]
Chronic Workload vs. Anaerobic sprint test peak power	$r = 0.09$; $p > 0.05$	[164]
Chronic Workload vs. Change of direction	$r = -0.43$; $p < 0.05$*	[164]
Aerobic conditioning training load vs. 10m sprint	$r = -0.47$; $R^2 = 0.22$	[140]
Aerobic conditioning training load vs. 10m sprint momentum	$r = 0.51$; $R^2 = 0.26$	[140]
Aerobic conditioning training load vs. 20m sprint	$r = -0.65$; $R^2 = 0.42$	[140]
Aerobic conditioning training load vs. 20m sprint momentum	$r = 0.52$; $R^2 = 0.28$	[140]
Aerobic conditioning training load vs. Change of direction	$r = 0.14$; $R^2 = 0.02$	[140]
Aerobic conditioning training load vs. CMJ	$r = 0.19$; $R^2 = 0.03$	[140]
Aerobic conditioning training load vs. Power pass	$r = 0.03$; $R^2 = 0.01$	[140]
Aerobic conditioning training load vs. Prone Yo-Yo IR1	$r = 0.01$; $R^2 = 0.00$	[140]
Intensification period vs. CMJ	$g = 0.11$ [90% CI -0.37, 0.59]	[130]
Intensification period vs. left hip flexibility	$g= -0.11$ [90% CI -0.59, 0.85]	[130]
Intensification period vs. push ups	$g = -0.03$ [90% CI -0.51, 0.46]	[130]
Intensification period vs. right hip flexibility	$g = 0.07$ [90% CI -0.7, 0.49]	[130]
Intensification period vs. sit ups	$g = 0.13$ [90% CI -0.36, 0.61]	[130]
Monotony vs. Anaerobic sprint rest average power	$r = 0.08$; $p > 0.05$	[164]
Monotony vs. Anaerobic sprint test fatigue index	$r = -0.1$; $p > 0.05$	[164]
Monotony vs. Anaerobic sprint test minimum power	$r = -0.15$; $p > 0.05$	[164]
Monotony vs. Anaerobic sprint test peak power	$r = 0.08$; $p > 0.05$	[164]
Monotony vs. Change of direction	$r = -0.17$; $p > 0.05$	[164]
Monotony vs. Lactate minimum speed (Competitive period)	$\rho = -0.31$; $p > 0.05$	[135]
Monotony vs. Lactate minimum speed (General period)	$\rho = 0.51$; $p > 0.05$	[135]
Monotony vs. Lactate minimum speed (Specific period)	$\rho = 0.14$; $p > 0.05$	[135]
Monotony vs. Repeated sprint ability (Competition period)	$\rho = -0.63$; $p < 0.05$*	[135]
Monotony vs. Repeated sprint ability (Competition period)	$\rho = -0.52$; $p < 0.05$*	[135]
Monotony vs. Repeated sprint ability (General period)	$\rho = -0.17$; $p > 0.05$	[135]
Monotony vs. Repeated sprint ability (Specific period)	$\rho = -0.36$; $p > 0.05$	[135]

Monotony vs. Repeated sprint ability (Specific period)	$\rho = -0.58$; $p < 0.05$*	[135]
Montony vs. Repeated sprint ability (General period)	$\rho = -0.16$; $p > 0.05$	[135]
On court training load on tour vs. 10m sprint	r = 0.45; $p \leq 0.05$*	[161]
On court training load on tour vs. 10x20m repeated sprint ability	r = 0.27; $p > 0.05$	[161]
On court training load on tour vs. 20m sprint	r = 0.52; $p \leq 0.05$*	[161]
On court training load on tour vs. 5-0-5 Left	r = 0.24; $p > 0.05$	[161]
On court training load on tour vs. 5-0-5 Right	r = 0.09; $p > 0.05$	[161]
On court training load on tour vs. 5m sprint	r = 0.26; $p > 0.05$	[161]
On court training load on tour vs. CMJ	r = 0.04; $p > 0.05$	[161]
On court training load on tour vs. Multi-Stage Fitness test	r = –0.48; $P \leq 0.05$*	[161]
On court training load on tour vs. Single leg CMJ (Dominant)	r = –0.06; $p > 0.05$	[161]
On court training load on tour vs. Single leg CMJ (Non-dominant)	r = –0.06; $p > 0.05$	[161]
On court training load pre tour vs. 10m sprint	r = –0.07; $p > 0.05$	[161]
On court training load pre tour vs. 10x20m repeated sprint ability	r = –0.37; $p \leq 0.05$*	[161]
On court training load pre tour vs. 20m sprint	r = –0.13; $p > 0.05$	[161]
On court training load pre tour vs. 5-0-5 Left	r = 0.25; $p > 0.05$	[161]
On court training load pre tour vs. 5-0-5 Right	r = 0.16; $p > 0.05$	[161]
On court training load pre tour vs. 5m sprint	r = –0.10; $p > 0.05$	[161]
On court training load pre tour vs. CMJ	r = 0.40; $p \leq 0.05$*	[161]
On court training load pre tour vs. Multi-Stage Fitness test	r = –0.19; $p > 0.05$	[161]
On court training load pre tour vs. Single leg CMJ (Dominant)	r = 0.16; $p > 0.05$	[161]
On court training load pre tour vs. Single leg CMJ (Non-dominant)	r = 0.07; $p > 0.05$	[161]
Resistance training load vs. 10m sprint	r = -0.52; $R^2 = 0.273$	[140]
Resistance training load vs. 10m sprint momentum	r = 0.12; $R^2 = 0.014$	[140]
Resistance training load vs. 20m sprint	r = -0.49; $R^2 = 0.236$	[140]
Resistance training load vs. 20m sprint momentum	r = 0.01; $R^2 = 0$	[140]
Resistance training load vs. Change of direction	r = 0.42; $R^2 = 0.18$	[140]
Resistance training load vs. CMJ	r = 0.51; $R^2 = 0.26$	[140]

Resistance training load vs. Power pass	$r = 0.40$; $R^2 = 0.16$	[140]
Resistance training load vs. Prone Yo-Yo IR1	$r = 0.04$; $R^2 = 0.01$	[140]
S&C training load on tour vs. 10m sprint	$r = -0.07$; $p > 0.05$	[161]
S&C training load on tour vs. 10x20m repeated sprint ability	$r = 0.36$; $p \leq 0.05$*	[161]
S&C training load on tour vs. 20m sprint	$r = -0.08$; $p > 0.05$	[161]
S&C training load on tour vs. 5-0-5 Left	$r = 0.01$; $p > 0.05$	[161]
S&C training load on tour vs. 5-0-5 Right	$r = 0.01$; $p > 0.05$	[161]
S&C training load on tour vs. 5m sprint	$r = 0.27$; $p > 0.05$	[161]
S&C training load on tour vs. CMJ	$r = -0.19$; $p > 0.05$	[161]
S&C training load on tour vs. Multi-Stage Fitness test	$r = -0.04$; $p > 0.05$	[161]
S&C training load on tour vs. Single leg CMJ (Dominant)	$r = -0.12$; $p > 0.05$	[161]
S&C training load on tour vs. Single leg CMJ (Non-dominant)	$r = 0.28$; $p > 0.05$	[161]
S&C training load pre tour vs. 10m sprint	$r = -0.11$; $p > 0.05$	[161]
S&C training load pre tour vs. 10x20m repeated sprint ability	$r = -0.11$; $p > 0.05$	[161]
S&C training load pre tour vs. 20m sprint	$r = -0.09$; $p > 0.05$	[161]
S&C training load pre tour vs. 5-0-5 Left	$r = 0.25$; $p > 0.05$	[161]
S&C training load pre tour vs. 5-0-5 Right	$r = 0.32$; $p > 0.05$	[161]
S&C training load pre tour vs. 5m sprint	$r = -0.06$; $p > 0.05$	[161]
S&C training load pre tour vs. CMJ	$r = 0.03$; $p > 0.05$	[161]
S&C training load pre tour vs. Multi-Stage Fitness test	$r = -0.02$; $p > 0.05$	[161]
S&C training load pre tour vs. Single leg CMJ (Dominant)	$r = 0.1$; $p > 0.05$	[161]
S&C training load pre tour vs. Single leg CMJ (Non-dominant)	$r = 0.06$; $p > 0.05$	[161]
Skill training load vs. 10m sprint	$r = -0.71$; $R^2 = 0.51$	[140]
Skill training load vs. 10m sprint momentum	$r = 0.35$; $R^2 = 0.12$	[140]
Skill training load vs. 20m sprint	$r = -0.79$; $R^2 = 0.62$	[140]
Skill training load vs. 20m sprint momentum	$r = 0.27$; $R^2 = 0.07$	[140]
Skill training load vs. Change of direction	$r = 0.20$; $R^2 = 0.04$	[140]
Skill training load vs. CMJ	$r = 0.60$; $R^2 = 0.36$	[140]

Skill training load vs. Power pass	r = 0.22; R^2 = 0.05	[140]
Skill training load vs. Prone Yo-Yo IR1	r = 0.11; R^2 = 0.01	[140]
Skill training load vs. Prone Yo-Yo IR1	r = 0.11; R^2 = 0.01	[140]
Strain vs. Anaerobic sprint rest average power	r = -0.10; $p > 0.05$	[164]
Strain vs. Anaerobic sprint test fatigue index	r = 0.35; $p > 0.05$	[164]
Strain vs. Anaerobic sprint test minimum power	r = 0.18; $p > 0.05$	[164]
Strain vs. Anaerobic sprint test peak power	r = -0.13; $p > 0.05$	[164]
Strain vs. Change of direction	r = 0.42; $p < 0.05$*	[164]
Strain vs. Lactate minimum speed (Competitive period)	ρ = -0.36; p > 0.05	[135]
Strain vs. Lactate minimum speed (General period)	ρ = 0.42: p > 0.05	[135]
Strain vs. Lactate minimum speed (Specific period)	ρ = 0.07; $p > 0.05$	[135]
Strain vs. Repeated sprint ability (Competition period)	ρ = -0.42 p > 0.05	[135]
Strain vs. Repeated sprint ability (Competition period)	ρ = 0.53; $p < 0.05$*	[135]
Strain vs. Repeated sprint ability (General period)	ρ = -0.10; $p > 0.05$	[135]
Strain vs. Repeated sprint ability (General period)	ρ = 0.12; $p > 0.05$	[135]
Strain vs. Repeated sprint ability (Specific period)	ρ = 0.37; $p > 0.05$	[135]
Strain vs. Repeated sprint ability (Specific period)	ρ = -0.34; p > 0.05	[135]
Sum of perceived exertion Under 15 vs. 15m sprint	r = 0.57 (90%CI ± 0.48)	[167]
Sum of perceived exertion Under 15 vs. 5m sprint	r = 0.67 (90%CI ± 42	[167]
Sum of perceived exertion Under 15 vs. CMJ	r = -0.70 (90%CI ± 0.4)	[167]
Sum of perceived exertion Under 15 vs. T-Test	r = 0.53 (90%CI ± 0.51)	[167]
Sum of perceived exertion Under 15 vs. Yo-Yo IR1	r = -0.78 (90%CI ± 0.32	[167]
Sum of perceived exertion Under 16 vs. 15m sprint	r = 0.44 (90%CI ± 0.47)	[167]
Sum of perceived exertion Under 16 vs. 5m sprint	r = 0.47 (90%CI ± 0.47)	[167]
Sum of perceived exertion Under 16 vs. CMJ	r = 0.39 (90%CI ± 0.49)	[167]
Sum of perceived exertion Under 16 vs. T-Test	r = 0.11 (90%CI ± 0.55)	[167]
Sum of perceived exertion Under 16 vs. Yo-Yo IR1	r = 0.22 (90%CI ± 0.51)	[167]
Taper period vs. CMJ	g = -0.11 [90% CI -0.58, 0.38]	[130]

Taper period vs. left hip flexibility	g = 0.42 [90% CI -0.39, 1.23]	[130]
Taper period vs. push ups	g = 0.61 [90% CI 1.09, 0.11] (sic)	[130]
Taper period vs. right hip flexibility	g = 0.24 [90% CI -0.54, 1.02]	[130]
Taper period vs. sit ups	g = 0.8 [90% CI 0.29, 1.29]*	[130]
Total Tennis training load vs. 10m sprint	r = 0.45	[161]
Total Tennis training load vs. 20m sprint	r = 0.52	[161]
Total Tennis training load vs. Multi-Stage Fitness test	r = -0.44	[161]
Total training load vs. Change of direction	r = 0.32; R^2 = 0.105	[140]
Total training load vs. CMJ	r = 0.55; R^2 = 0.306	[140]
Total training load vs. Power pass	r = 0.29; R^2 = 0.084	[140]
Training load in overload period vs. Yo-Yo IR1	d = -1.48 [0/0/100]; $p < 0.016$	[142]
Training load in taper vs. Yo-Yo IR1	d = 1.83 [100/0/0]; $p < 0.016$	[142]
Training load on tour vs. 10m sprint	r = 0.38; p ≤ 0.05*	[161]
Training load on tour vs. 10x20m repeated sprint ability	r = 0.36; $p > 0.05$	[161]
Training load on tour vs. 20m sprint	r = 0.44; $p \leq 0.05$*	[161]
Training load on tour vs. 5-0-5 Left	r = 0.22; $p > 0.05$	[161]
Training load on tour vs. 5-0-5 Right	r = 0.08; $p > 0.05$	[161]
Training load on tour vs. 5m sprint	r = 0.31; $p > 0.05$	[161]
Training load on tour vs. CMJ	r = –0.02; $p > 0.05$	[161]
Training load on tour vs. Multi-Stage Fitness test	r = –0.40; $p \leq 0.05$*	[161]
Training load on tour vs. Single leg CMJ (Dominant)	r = –0.09; $p > 0.05$	[161]
Training load on tour vs. Single leg CMJ (Non-dominant)	r = 0.03; $p > 0.05$	[161]
Training load Pre tour vs. 10m sprint	r = –0.08; $p > 0.05$	[161]
Training load Pre tour vs. 10x20m repeated sprint ability	r = –0.36; $p > 0.05$	[161]
Training load Pre tour vs. 20m sprint	r = –0.14; $p > 0.05$	[161]
Training load Pre tour vs. 5-0-5 Left	r = 0.27; $p > 0.05$	[161]
Training load Pre tour vs. 5-0-5 Right	r = 0.17; $p > 0.05$	[161]
Training load Pre tour vs. 5m sprint	r = –0.10; $p > 0.05$	[161]

Training load Pre tour vs. CMJ	r = 0.38; $p \leq 0.05$*	[161]
Training load pre tour vs. Multi-Stage Fitness test	r = –0.18; $p > 0.05$	[161]
Training load Pre tour vs. Single leg CMJ (Dominant)	r = 0.17; $p > 0.05$	[161]
Training load Pre tour vs. Single leg CMJ (Non-dominant)	r = 0.07; $p > 0.05$	[161]
Training load Under 15 vs. 15m sprint	r = 0.55 (90%CI ± 0.5)	[167]
Training load Under 15 vs. 5m sprint	r = 0.64 (90%CI ± 0.44)	[167]
Training load Under 15 vs. CMJ	r = -0.65 (90%CI ± 0.43)	[167]
Training load Under 15 vs. T-Test	r = 0.52 (90%CI ± 0.51)	[167]
Training load Under 15 vs. Yo-Yo IR1	r = -0.78 (90%CI ± 0.32)	[167]
Training load Under 16 vs. 15m sprint	r = 0.42 (90%CI ± 0.48)	[167]
Training load Under 16 vs. 5m sprint	r = 0.45 (90%CI ± 0.47)	[167]
Training load Under 16 vs. CMJ	r = 0.39 (90%CI ± 0.49)	[167]
Training load Under 16 vs. T-Test	r = 0.10 (90%CI ± 0.55)	[167]
Training load Under 16 vs. Yo-Yo IR1	r = 0.22 (90%CI ± 0.51)	[167]
Training load vs. 10m sprint	r = -0.70; $R^2 = 0.488$	[140]
Training load vs. 10m Sprint	p = 0.70	[164]
Training load vs. 10m sprint momentum	r = 0.36; $R^2 = 0.13$	[140]
Training load vs. 20m sprint	r = -0.77; $R^2 = 0.60$	[140]
Training load vs. 20m sprint momentum	r = 0.29; $R^2 = 0.08$	[140]
Training load vs. 30m Sprint	p = 0.51	[164]
Training load vs. Anaerobic sprint rest average power	p = 0.93	[164]
Training load vs. Anaerobic sprint test fatigue index	p = 0.67	[164]
Training load vs. Anaerobic sprint test minimum power	p = 0.23	[164]
Training load vs. Anaerobic sprint test peak power	p = 0.34	[164]
Training load vs. Change in MAS	r = 0.37 [95%CI -0.27, 0.88]; $R^2 = 0.24$ [0.00 - 0.55]	[182]
Training load vs. Change in velocity at 2 mmol.l	r = -0.17 [95%CI -0.77, 0.50]; $R^2 = 0.12$ [0.00 - 0.40]	[182]

Training load vs. Change in velocity at 4 mmol.l	$r = -0.16$ [95%CI -0.76, 0.51]; $R^2 = 0.12$ [0.00 - 0.39]	[182]
Training load vs. CMJ	$d = -0.9$	[175]
Training load vs. Heart rate at 2mmol.l - L	$r = 0.20$; $p > 0.05$	[63]
Training load vs. Heart rate at 4mmol.l - L	$r = 0.15$; $p > 0.05$	[63]
Training load vs. Lactate minimum speed (Competitive period)	$\rho = -0.18$; $p > 0.05$	[135]
Training load vs. Lactate minimum speed (General period)	$\rho = 0.55$; $p < 0.05$*	[135]
Training load vs. Lactate minimum speed (General period)	$\rho = 0.01$; $p > 0.05$	[135]
Training load vs. Lactate minimum speed (Specific period)	$\rho = -0.10$; $p > 0.05$	[135]
Training load vs. MAS	$r = 0.22$ (90%CI -0.26, 0.62)	[66]
Training load vs. Modified 5-0-5	p = 0.16	[164]
Training load vs. MSS	$r = 0.37$ (90%CI -0.11, 0.71)	[66]
Training load vs. Prone Yo-Yo IR1	$r = 0.07$; $R^2 = 0.005$	[140]
Training load vs. Repeated sprint ability (Competition period)	$\rho = 0.35$; $p > 0.05$	[135]
Training load vs. Repeated sprint ability (Competition period)	$\rho = -0.26$; $p > 0.05$	[135]
Training load vs. Repeated sprint ability (General period)	$\rho = 0.12$; $p > 0.05$	[135]
Training load vs. Repeated sprint ability (General period)	$\rho = 0.02$; $p > 0.05$	[135]
Training load vs. Repeated sprint ability (Specific period)	$\rho = -0.18$; $p > 0.05$	[135]
Training load vs. Repeated sprint ability (Specific period)	$\rho = -0.12$; $p > 0.05$	[135]
Training load vs. Velocity at 2mmol.l	$R = 0.11$ [99%CI -0.29, 0.51]; $p = 0.66$	[177]
Training load vs. Velocity at 2mmol.l - L	$r = 0.13$; $p > 0.05$	[63]
Training load vs. Velocity at 4mmol.l	$R = 0.07$ [99%CI -0.13, 0.27]; $p = 0.77$	[177]
Training load vs. Velocity at 4mmol.l - L	$r = 0.40$; $p > 0.05$	[63]
Training load vs. Velocity at $\dot{V}O_{2max}$	$R = 0.14$ [99%CI -0.26, 0.54]; $p = 0.59$	[177]
Training load vs. $\dot{V}O_{2max}$	$R = 0.12$ [99%CI -0.30, 0.54]; $p = 0.65$	[177]

*Statistically significant result; ^{z}Inconsistent or erroneous datum; CMJ = Countermovement jump; CMJA = Countermovement jump with arm swing; sRPE = Session ratings of perceived exertion; sRPEres = Session ratings of perceived exertion respiratory; sRPEmus = Session ratings of perceived muscular; MAS = Maximal aerobic speed; MSS = Maximal sprint speed; bTRIMP = Banisters training impulse; eTRIMP = Edwards training impulse; iTRIMP = Individual training impulse; luTRIMP = Lucia’s training impulse; TeamTRIMP = Team training impulse; S&C = Strength and conditioning.

4.3.6 Internal training loads and injury

Table 4.8 presents the relationships between internal training loads and injury. Ten studies found significant relationships between internal training load and injury [128, 134, 139, 154, 160, 163, 166, 168, 174, 181], whilst one found no relationship [149]. Studies used a number of different definitions of injury, including reporting of a physical complaint or medical attention [128, 134, 160], time-loss injuries [139, 154, 163, 166, 174, 181], and time loss greater than three weeks [149]. However, when pooling all the contributing findings from included studes, only 25% of contributing findings showed a relationship between internal training loads and injury.

The evidence of a relationship between sRPE and injury risk was limited. There were positive [134, 160, 166, 181], non-significant [139, 174], and variable [154, 168] relationships between one-week sRPE and injury risk. Two-week training load and injury had positive [128], and non-significant [128, 154, 166] results. No significant relationship was seen for three- and four-week training load, annual high-intensity training load, or annual training load and injury risk [139, 154, 166]. Daily training load [181], prior days training load [181], and individual sessional load [154] were all found to be positively related to injury risk.

Some studies investigated the change in training loads using statistical methods such as the acute to chronic work ratio (ACWR), monotony, and strain. These alternative methods of analysing internal training loads had inconsistent relationships with injury risk. Results were non-significant [128, 139, 154, 163, 166, 174, 181] and positive [150, 151, 154, 163] for ACWR; non-significant findings [134, 154, 166], and positive [134, 166] for strain and monotony.

Table 4.8. Results of relationship between internal training load and change in injury risk

Monitoring method	Measure vs. Injury risk	Relationship	Reference
Heart rate	eTRIMP	1 Unit = increase in injury risk; *p* = 0.014*	[172]
Novel scale	Annual high intensity	*p* = 0.06	[149]
	Annual training load	*p* = 0.10	[149]
	Average Hours	*p* = 0.36	[149]
	Total high intensity	*p* = 0.16	[149]
	Total training hours	*p* = 0.54	[149]
	Total training load	*p* = 0.24	[149]
sRPE	1 week load	RR = 1.11 [95%CI 0.84, 1.50]; *p* = 0.44	[139]
	1 week load	OR = 1.00 [90%CI 0.99, 1.00]	[174]
	1 week load	OR = 0.56 [95%CI 0.42, 0.73]; *p* < 0.001*	[154]
	1 week load	OR = 1.43 [95%CI 1.07, 1.92]; *p* = 0.015*	[154]
	1 week differential load	*p* = 0.86	[168]
	1 week EWMA load	RR = 1.88 [95%CI 1.21 – 1.91], *p* = 0.005	[168]
	1 week load > 898 AU	OR = 2.75 [95%CI 1.00, 7.59]; *p* = 0.05*	[166]
	1 week load >6844 AU (<3330 reference)	RR = 2.12 [95%CI 0.77, 5.85]	[160]
	1 week load >6844 AU (3330 - 4994 reference)	RR = 1.93 [95%CI 0.90, 4.15]	[160]
	1 week load >6844 AU (4995 - 6844 reference)	RR = 2.29 [95%CI 1.03, 5.07]*	[160]
	1 week load 3330-4994 AU (<3330 reference)	RR = 1.10 [95%CI 0.40, 2.98]	[160]
	1 week load 4995-6844 AU (<3330 reference)	RR = 0.93 [95%CI 0.33, 2.59]	[160]
	1 week load 4995-6844 AU (3330 - 4994 reference)	RR = 0.85 [95%CI 0.39, 1.84]	[160]
	1 week load	OR = 1.62 [CI 1.16, 2.29]; *p* = 0.005*	[181]
	1 week load vs. Overuse Injury	OR = 1.01 (95%CI 1.00, 1.02); *p* ≥ 0.05	[134]
	1 week load vs. Traumatic injury	OR = 1.01 (95%CI 1.00, 1.02); *p* < 0.05*	[134]
	2 week ACWR	RR = 0.99 [95%CI 0.90, 1.09]; *p* = 0.82	[139]
	2 week load	RR = 1.03 [95%CI 0.77, 1.38]; *p* = 0.85	[139]

2 week load	OR = 1.01 [95%CI 0.91, 1.11]; $p = 0.90$	[154]
2 week training load > 1713 AU	OR = 2.57 [95%CI 0.94, 7.07]; $p = 0.07$	[166]
3 week ACWR	RR = 1.00 [95%CI 0.95, 1.06]; $p = 0.91$	[139]
3 week load	RR = 0.97 [95%CI 0.74, 1.28]; $p = 0.82$	[139]
3 week load	OR = 0.99 [95%CI 0.89, 1.11]; $p = 0.90$	[154]
3 week training load > 2376 AU	OR = 2.57 [95%CI 0.94, 7.07]; $p = 0.07$	[166]
4 week ACWR	RR = 1.01 [95%CI 0.96, 1.07]; $p = 0.73$	[139]
4 week ACWR	HR = 2.76 [95%CI 1.58, 4.82]; $p < 0.01$*	[163]
4 week ACWR	OR = 0.16 [90%CI 0.01, 1.84]	[174]
4 week ACWR	OR = 1.20 [95%CI 0.87, 1.64]; $p = 0.26$	[154]
4 week ACWR	OR = 0.68 [95%CI 0.40, 0.96]; $p = 0.03$*	[154]
4 week ACWR > 1.3	OR = 0.40 [95%CI 0.13, 1.22]; $p = 0.11$	[166]
4 week ACWR vs. Injury	OR = 1.59 [CI 1.1, 2.5]; $p = 0.03$*	[181]
4 week load	RR = 1.00 [95%CI 0.76, 1.33]; $p = 0.97$	[139]
4 week load	OR = 0.92 [95%CI 0.83, 1.03]; $p = 0.13$	[154]
4 week load > 2996 AU	OR = 2.57 [95%CI 0.94, 7.07]; $p = 0.07$	[166]
4 week load	OR = 1.13 [CI 0.75, 1.67]; $p = 0.55$	[181]
Daily Training load	OR = 1.98 [CI 1.43, 2.78]; $p < 0.01$*	[181]
Daily Training load	OR = 1.91 [CI 1.40, 2.63]; $p < 0.01$*	[181]
High (>0.35) 3 day Training load z-score	RR = 2.4 [1.57, 3.66]; $p < 0.001$*	[128]
High (>0.67) 14 day Training load z-score	RR = 1.89 [1.26, 2.85]; $p = 0.01$*	[128]
High (>1.30) EWMA ACWR	RR = 1.01 [0.65, 1.58]; Unclear; $p = 0.96$	[128]
High 1 week Training load	RR = 1.65; $p < 0.05$	[132]
High 2 week Training load	RR = 1.03; $p > 0.05$	[132]
High 3 week Training load	RR = 1.09; $p > 0.05$	[132]
High 4 week Training load	RR = 1.2; $p > 0.05$	[132]
High 4 Week Training load ACWR	RR = 1.01; $p > 0.05$	[132]
High 4 Week Training load ACWR with high chronic workload	RR = 0.43; $p > 0.05$	[132]

High 4 Week Training load ACWR with low chronic workload	RR = 1.59; $p > 0.05$	[132]
Low 1 week Training load	RR = 0.27; $p < 0.05$	[132]
Low 2 week Training load	RR = 0.5; $p > 0.05$	[132]
Low 3 week Training load	RR = 0.55; $p > 0.05$	[132]
Low 4 week Training load	RR = 0.75; $p > 0.05$	[132]
Low 4 Week Training load ACWR	RR = 0.84; $p > 0.05$	[132]
Low 4 Week Training load ACWR with high chronic workload	RR = 0.81; $p > 0.05$	[132]
Low 4 Week Training load ACWR with low chronic workload	RR = 0.37; $p > 0.05$	[132]
Medium (<0.45 - 0.35) 3 day Training load z-score	RR = 1.18 [0.73, 1.93]; $p = 0.56$	[128]
Medium (-0.40 - 0.67) 14 day Training load z-score	RR = 1.18 [0.82, 1.71]; $p = 0.46$	[128]
Medium (0.80-1.30) EWMA ACWR	RR = 0.99 [0.64, 1.56]; $p = 0.99$	[128]
Moderate-high 1 week Training load	RR = 0.98; $p > 0.05$	[132]
Moderate-high 2 week Training load	RR = 1.38; $p > 0.05$	[132]
Moderate-high 3 week Training load	RR = 1.39; $p > 0.05$	[132]
Moderate-high 4 week Training load	RR = 1.12; $p > 0.05$	[132]
Moderate-high 4 Week Training load ACWR	RR = 1.34; $p > 0.05$	[132]
Moderate-high 4 Week Training load ACWR with high chronic workload	RR = 1.34; $p > 0.05$	[132]
Moderate-high 4 Week Training load ACWR with low chronic workload	RR = 1.16; $p > 0.05$	[132]
Moderate-low 1 week Training load	RR = 1.45; $p > 0.05$	[132]
Moderate-low 2 week Training load	RR = 1.07; $p > 0.05$	[132]
Moderate-low 3 week Training load	RR = 0.98; $p > 0.05$	[132]
Moderate-low 4 week Training load	RR = 1.01; $p > 0.05$	[132]
Moderate-low 4 Week Training load ACWR	RR = 1.15; $p > 0.05$	[132]
Moderate-low 4 Week Training load ACWR with high chronic workload	RR = 1.22; $p > 0.05$	[132]
Moderate-low 4 Week Training load ACWR with low chronic workload	RR = 1.15; $p > 0.05$	[132]
Monotony	OR = 1.01 [95%CI 0.92, 1.11]; $p = 0.843$	[154]
Monotony > 0.53	OR = 6.16 [95%CI 1.58, 24.06]; $p = 0.01$*	[166]
Monotony > 0.53	OR = 4.17 [95%CI 1.48, 11.72]; $p = 0.01$*	[166]

Monotony vs. Overuse Injury	OR = 0.84 (95%CI 0.25, 2.76); $p \geq 0.05$	[134]
Monotony vs. Traumatic Injury	OR = 2.59 (95%CI 1.22, 5.50); $p < 0.05$*	[134]
Prior day training load vs. Injury	OR = 1.38 [CI 1.01, 1.88]; $p = 0.040$*	[181]
Prior day training load	OR = 1.42 [CI 1.04, 1.95]; $p = 0.027$*	[181]
Session load	OR = 0.64 [95%CI 0.49, 0.83] p < 0.01*	[154]
Session load	OR = 1.44 [95%CI 1.11, 1.88]; $p < 0.01$*	[154]
Strain	OR = 0.63 [95%CI 0.45, 0.88]; $p < 0.01$*	[154]
Strain > 809 AU	OR = 0.35 [95%CI 0.05, 2.32]; $p = 0.28$	[166]
Strain	OR = 1.41 [95%CI 1.02, 1.93]; $p = 0.03$*	[154]
Strain > 809 AU	OR = 2.49 [95%CI 0.79, 7.88]; $p = 0.12$	[166]
Strain vs. Overuse Injury	OR = 1.00 (95%CI 1.00, 1.01); $p \geq 0.05$	[134]
Strain vs. Traumatic injury	OR = 1.01 (95%CI 1.00, 1.01); $p < 0.05$*	[134]
Very high 1 week Training load	RR = 2; $p > 0.05$	[132]
Very high 2 week Training load	RR = 1.93; $p > 0.05$	[132]
Very high 3 week Training load	RR = 1.59; $p > 0.05$	[132]
Very high 4 week Training load	RR = 1.84; $p > 0.05$	[132]
Very high 4 Week Training load ACWR	RR = 1.17; $p > 0.05$	[132]
Very high 4 Week Training load ACWR with high chronic workload	RR = 2.67; $p > 0.05$	[132]
Weekly change in load	RR = 1.00 [95%CI 0.96, 1.04]; $p = 0.93$	[139]
Weekly change in load	OR = 1.00 [95%CI 0.93, 1.07]; $p = 0.95$	[154]
Weekly change in load > 410 AU	OR = 3.70 [95%CI 0.87, 15.75]; $p = 0.41$	[166]
Weekly change in load > 410 AU	OR = 3.27 [95%CI 1.15, 9.32]; $p = 0.03$*	[166]
Weekly percentage change in load	OR = 0.94 [95%CI 0.86, 1.03]; $p = 0.21$	[154]

*Statistically significant result; ^{z}Inconsistent or erroneous datum; EWMA = exponentially weighted moving average; AU = arbitrary units; ACWR = acute to chronic work to rest ratio; OR = Odds ratio; RR = Relative risk.

4.3.7 Internal training loads and illness

Table 4.9 presents the relationships between internal training loads and illness. Seven studies investigated the relationship between internal training load and illness [134-136, 144, 181, 184]. Both non-significant [134-136, 144, 184] and positive [181] relationships were reported for sRPE. The only study that investigated the relationship between HR and injury risk found a positive relationship [172].

Table 4.9. Results of relationship between internal training load and illness

Monitoring method	Measure	Relationship	Reference
sRPE	Intensification and taper periods vs. URTI symptoms	$\chi2 = 2.81$; $p = 0.24$	[130]
	1 week load vs. Illness	OR = 1.00 (95%CI 0.99, 1.02); $p \geq 0.05$	[134]
	Monotony vs. Illness	OR = 2.52 (95%CI 0.79, 8.08); $p \geq 0.05$	[134]
	Strain vs. Illness	OR = 1.00 (95%CI 1.00, 1.01); $p \geq 0.05$	[134]
	Training load vs. URTI incidence (Period 1)	$\rho = 0.09$; $p > 0.05$	[135]
	Training load vs. URTI incidence (Period 2)	$\rho = -0.20$; $p > 0.05$	[135]
	Training load vs. URTI incidence (Period 3)	$\rho = -0.19$; $p > 0.05$	[135]
	Training load vs. URTI severity (Period 1)	$\rho = -0.07$; $p > 0.05$	[135]
	Training load vs. URTI severity (Period 2)	$\rho = -0.15$; $p > 0.05$	[135]
	Training load vs. URTI severity (Period 3)	$\rho = 0.06$; $p > 0.05$	[135]
	Week 1 Weekly load vs. URTI symptoms	$r = 0.3$; $p = 0.34$	[136]
	Week 2 Weekly load vs. URTI symptoms	$r = 0.22$; $p = 0.48$	[136]
	Week 3 Weekly load vs. URTI symptoms	$r = 0.18$; $p = 0.57$	[136]
	Week 4 Weekly load vs. URTI symptoms	$r = 0.41$; $p = 0.18$	[136]
	Week 5 Weekly load vs. URTI symptoms	$r = 0.41$; $p = 1.18$	[136]
	Week 6 Weekly load vs. URTI symptoms	$r = 0.02$; $p = 0.94$	[136]
	Week 7 Weekly load vs. URTI symptoms	$r = 0.07$; $p = 0.81$	[136]
	Week 8 Weekly load vs. URTI symptoms	$r = 0.02$; $p = 0.94$	[136]
	Week 1 Weekly monotony vs. URTI symptoms	$r = 0.1$; $p = 0.75$	[136]

Week 2 Weekly monotony vs. URTI symptoms	r = 0.05; $p = 0.89$	[136]
Week 3 Weekly monotony vs. URTI symptoms	r = 0.04; $p = 0.91$	[136]
Week 4 Weekly monotony vs. URTI symptoms	r = 0.45; $p = 0.15$	[136]
Week 5 Weekly monotony vs. URTI symptoms	r = 0.44; $p = 0.15$	[136]
Week 6 Weekly monotony vs. URTI symptoms	r = 0.27; $p = 0.40$	[136]
Week 7 Weekly monotony vs. URTI symptoms	r = 0.13; $p = 0.69$	[136]
Week 8 Weekly monotony vs. URTI symptoms	r = 0.18; $p = 0.57$	[136]
Week 1 Weekly strain vs. URTI symptoms	r = 0.00; $p = 0.99$	[136]
Week 2 Weekly strain vs. URTI symptoms	r = 0.07; $p = 0.81$	[136]
Week 3 Weekly strain vs. URTI symptoms	r = 0.04; $p = 0.89$	[136]
Week 4 Weekly strain vs. URTI symptoms	r = 0.39; $p = 0.20$	[136]
Week 5 Weekly strain vs. URTI symptoms	r = 0.49; $p = 0.10$	[136]
Week 6 Weekly strain vs. URTI symptoms	r = -0.17; $p = 0.59$	[136]
Week 7 Weekly strain vs. URTI symptoms	r = 0.18; $p = 0.58$	[136]
Week 8 Weekly strain vs. URTI symptoms	r = 0.18; $p = 0.58$	[136]
Week 1 overload training load vs. severity of URTI	$p > 0.05$	[144]
Week 2 overload training load vs. URTI	$p > 0.05$	[144]
Week 1 taper training load vs. severity of URTI	$p > 0.05$	[144]
Week 1 taper training load vs. severity of URTI	$p > 0.05$	[144]
4 week load vs. Illness	OR = 1.54 [CI 1.13, 1.2.12(sic)); $p < 0.01$*^{z}	[181]
1 week load vs. Illness	OR = 1.50 [CI 1.13, 2.00]; $p < 0.01$*	[181]
4 week ACWR vs. Illness	OR = 1.10 [CI 0.79, 1.52]; $p = 0.59$	[181]

	Prior day training load vs. Illness	OR = 1.08 [CI 0.82, 1.41]; p = 0.57	[181]

*Statistically significant result; ^{z}Inconsistent or erroneous datum; ACWR = Acute to chronic work to rest ratio; URTI = Upper respiratory tract infection; OR = Odds ratio.

4.4 Discussion

The aim of this review was to detail the methods of reporting internal and external loads in adolescent athletes and use best-evidence synthesis to report their relationship with changes in physical qualities, injury, or illness. Common internal methods of monitoring load included sRPE, dRPE, HR, and novel scales of perceived intensity, while common external methods of monitoring load included GNSS, resistance training volume, training duration, throw count, and accelerometry. Findings showed there was moderate evidence of a relationship between resistance training volume load and strength, and between training duration and throw count and injury. However, all other relationships between training load and physical qualities, injury, or illness were limited or inconsistent. An indirect finding of this review was the common use of univariate statistical techniques to establish the load-response relationship in adolescent athletes. Whilst the findings of this review indicate limited evidence of most relationships between training load and changes in physical qualities, injury and/or illness, this may be due to highly complex interactions, as opposed to relationships not existing. For example, a number of factors outside of training load, such as sleep, stress, and maturation, will influence these relationships, but were not quantified. Based on the findings and interpretation of this review, it is recommended that researchers and practitioners should consider: (1) accounting for resistance training volume load when monitoring strength training; (2) monitor training duration, and throws, if appropriate, for potential increases in injury risk; (3) assessing factors, such as maturation, that may influence how adolescent athletes respond to load; and (4) the appropriateness of the statistical methodology used to establish a load-response relationship.

4.4.1 Methods of monitoring training loads

A variety of internal and external loads monitoring tools were used, with the distribution between the use of internal (n = 32) and external (n = 35) methods of monitoring load close to even. The most commonly reported internal load monitoring tools were sRPE and heart rate, whilst the most commonly reported external tools were training duration and GNSS. The prevalence of these methods throughout the literature likely reflects the accessibility and relative ease with which they can be used. For example, sRPE gives an overview of the load of an entire training session and is commonly used to accumulate the load across multiple forms of training (e.g., field-based training and resistance training)*[28]*. Alternatively, heart rate and GNSS are becoming increasingly accessible for practitioners and help provide greater information regarding the distribution of intensity across a training session*[185]*. It should be acknowledged though that the use of heart rate and GNSS does have added expense due to the equipment involved which may limit its accessibility in adolescent sport. Furthermore, it does require additional expertise to collect and analyse the data appropriately [30]. Additionally, practitioners in adolescent settings are often constrained by both time and financial resources. Therefore, the methods of monitoring training load that are used throughout the adolescent literature may be an outcome of accessibility and relative ease of use rather than their relationship with changes in physical qualities, injury, or illness. Consequently, practitioners and researchers should carefully consider what the monitoring methods that are being used will add to a training environment and also whether the budget and expertise is available to help interpret the subsequent information.

4.4.2 Training loads and physical qualities

There was moderate evidence of a relationship between resistance training volume and strength, with three studies and 53% of the results indicating a positive relationship and no results indicating a negative relationship. Resistance training volume is a commonly used monitoring tool for strength training and represents the product of number of repetitions performed multiplied by the external load lifted [186]. Developing strength is recommended throughout all stages of adolescent development [2], as strength can be protective against injuries [110], facilitate performance [109], and underpins the development of other physical qualities, such as power [48]. Despite its importance, limited research (n = 4) has reported the relationship between training loads and strength. Additionally, all the studies were observational, limiting the ability for causal inference to be drawn. One of the studies found that a medium volume group had greater improvements in their snatch 1RM as compared to a low volume group, but not the high volume group [146]. These results indicate that there may be an upper limit to the load-response relationship, however, this has not been explored in detail in adolescent athletes. Nonetheless, volume load appears to demonstrate the strongest evidence for a relationship with changes in strength in adolescent athletes, and therefore warrants consideration by practitioners.

Increases in strength occur as a result of a combination of neural and muscular factors [187]. In pre peak height velocity (PHV) athletes, most strength based adaptations occur as a consequence of increased coordination [2, 188]. Strength increases seen from resistance training volume may be due to greater opportunities to practice. Post-PHV alterations in sex hormones enhance capacity for muscular adaptations, such as hypertrophy, to resistance training [2, 187]. Therefore, although the mechanisms are likely to differ, resistance training volume load should be a focus throughout all stages of adolescent athletic development. This may have practical implications in the programming and periodisation of resistance training in adolescent athletes. However, there is no evidence on how much resistance training volume should be prescribed, and future research should investigate the minimal effective doses.

There were no consistent relationships between training monitoring tools and aerobic fitness across eleven studies. The most commonly reported monitoring tools were sRPE (n = 8), GNSS devices (n = 5), and heart rate monitors (n = 6). Interestingly, a relationship between upper body resistance training load and 800m time was found in one study [183], however this relationship is likely to be spurious. Measures of gross volume or load, such as total distance and TRIMP's may not accurately represent the work performed, as they provide no information as to the distribution of volume or intensity. Some studies provided more informative measures of training load, such as distance and time between speed thresholds, however this did not improve any relationship [64, 66, 177]. The lack of consistent findings may be due to factors that mediate the response to aerobic training, such as maturation [189, 190], changes in body mass [191], and variety in the monitoring tools and testing methods used to assess aerobic fitness [12]. Previously, it has been shown that adolescent athletes may have altered responses to aerobic training throughout maturation [12]. However, no studies investigating the relationship between training loads and aerobic fitness reported the maturation level of the participants. Additionally, numerous training methods can enhance aerobic capacity, such as cross-training modalities (e.g., cycle or rowing ergometers), which may influence the effectiveness of some monitoring tools in accurately assessing overall training load (e.g., GNSS devices). Therefore, practitioners should consider external factors (e.g., maturation and body mass) that may influence aerobic capacity, and all forms of training that are being completed by the athlete.

The "Golidilocks" effect of the load-response relationship was evident in this review, with several studies finding that greater training loads were related to the decreased expression of physical qualities [67, 140, 161, 162, 167]. Given that the athletes in all studies were training throughout the period of investigation, it is unlikely de-training occurred. An alternative explanation for the decreased expression of physical qualities may be that excessive training loads and inadequate recovery caused substantial fatigue within the tested athletes [62], with studies reporting daily training loads as high as 1400 AU, equivalent to over four and a half hours of "hard" training (i.e., greater than an eight RPE on a CR10 scale) [28, 161]. Interestingly, two studies that found a negative relationship between sRPE and physical qualities were conducted with tennis players on international tours [161, 162]. Travel can influence performance and recovery through factors such as compromised sleep and nutrition [192, 193]. Therefore, although speculative, altered ability to recover may have played a mediating role in the results observed. Practitioners should also be cautious in interpreting a negative relationship between training load and physical qualities as advocating for a decrease in load, as this may hamper long-term athletic development. To state that more training results in decreased expression of physical capacity without offering solutions to reducing this risk, outside of simply reducing load, is unproductive. Instead, an increased focus should be placed on increasing or maintaining training loads whilst protecting athletes from injuries and fatigue by manipulating or accounting for factors that may mediate the load-response relationship.

4.4.3 Training loads and injury

There was moderate evidence of a relationship between training duration and throw count, and injury. However, there are limited applications of this finding as the relationship is likely due to increased exposure to risk. There were no other clear relationships between either internal or external monitoring tools and injury. Different metrics to assess distribution of training load were used, including the ACWR [128, 129, 132, 139, 154, 163, 174, 181], monotony [154, 166], and strain [154, 166]. Analysis of included studies was also effected by inconsistent definitions of injury. For example, methods of reporting injury included reporting of a physical complaint or medical attention [128, 134, 160], time-loss injuries or illness [139, 154, 163, 166, 174, 181], and time loss greater than three weeks [149]. Therefore, the inconsistent collection and analysis of methods used across different studies may unintentionally impede practitioners and researchers from drawing consensurs across investigations into training load and injury.

The ACWR was used across seven of the 12 studies that investigated the relationship between internal load measures, such as sRPE, and injury risk [128, 132, 139, 154, 163, 174, 181]. The ACWR is a monitoring method that quantifies the acute changes in training load (e.g., most recent 7 days) relative to chronic training load (e.g., most recent 28 days) [194]. However, there are inconsistent approaches to calculating the ACWR, including variable time frames and different statistical approaches, including exponentially weighted moving averages or rolling averages [195], and coupled or uncoupled chronic workloads [196]. The different statistical methods used to calculate ACWR can substantially alter the outcome, with one study demonstrating that quadratic calculation of the relationship between ACWR and injury was statistically significant, whereas linear was not [154]. Additionally, methodological pitfalls associated with the ACWR have been highlighted in studies that show that actual training loads confer no greater predictive value for injury risk than random chronic training loads [197]. Therefore, there is limited evidence for the use of ACWR as a metric to guide decisions around injury risk in an adolescent load monitoring program.

The monitoring tool with the strongest relationship between training load and injury was training duration, with 15 of 17 studies investigating this and 56% of contributing findings indicating a positive relationship. However, the use of various methods of reporting training duration makes it difficult to draw conclusions. For example, some studies examined training duration in the previous week [148], fortnight [133], over a season [157], weekly change in training duration [159], or duration relative to age [170, 173]. Whilst there were inconsistencies in the reporting mechanism, there remains moderate evidence that increased training duration in preceding periods increases injury risk. Superficially, this finding may have practical applications as training duration is simple to collect and easy to analyse [30]. However, this relationship is likely due to athletes having greater risk of injury simply due to increased exposure. It should be noted that despite the potential for a greater number of injuries, training is necessary to develop physical qualities, tactical knowledge, and technical skills. Finding a balance between training exposure and athletic development is needed. Whilst this may be the focus of future research, it may be difficult to generalise research-based results to specific populations, due to the multi-factorial nature of injury.

Overall, there was limited evidence of a relationship between training loads and injury risk in adolescent athletes. Furthermore, training load, when administered appropriately, may also be protective against injury, highlighting the “goldilocks” effect [115]. Therefore, practitioners should exercise caution when using singular training loads to assess injury risk in adolescent athletes in isolation from mediating factors. Other factors that should be considered when assessing injury risk may include sleep, stress, nutrition, biomechanics, and injury history [198]. However, this list is non-exhaustive, and the highly complex nature of injuries means that identifying, and accounting for all risk factors in an applied setting is difficult.

4.4.4 Training loads and illness

The evidence of a relationship between training loads and illness was limited or inconsistent with only six studies investigating these outcomes and only 4.6% of contributing findings indicating a relationship between training load and illness. The body interprets exercise as a stressor, similar to other psychological and physiological stressors [199]. Short term periods of stress are thought to be immunoprotective, whereas prolonged exposure to stress is immosuppressive [199]. Interestingly, the two studies that found a significant relationship between training load and illness had the longest observational period of any included studies (20 weeks and two seasons) [134, 181]. Given the delayed relationship between prolonged periods of high stress and illness, studies of insufficient length may have confounded the results of the best-evidence synthesis. However, it is not known what amount of exposure to excessive stress increases the risk of illlness. Additionally, given the general nature of stress, other stressors that adolescent athletes face, such as academic, social and performance pressure will likely contribute to this relationship, and should be accounted for [200].

4.5 Limitations and future directions

The results of this review provide important considerations for researchers and practitioners investigating and monitoring the training loads of adolescent athletes. However, there are limitations within this review that should be considered before implementing the findings. A limitation of the best-evidence synthesis methodology was the use of "vote-counting" criteria, with no weightings applied to the magnitude of the stimulus or strength of the relationship [127]. Vote-counting was used due to the lack of validated method of quantifying stimulus magnitude and strength of relationships across different load monitoring tools and heterogeneous statistical methodologies. While standardisation of reporting training load metrics may assist in facilitating future meta-analysis, it is unlikely that a consistent framework will be universally adopted, due to barriers such as variation in the appropriateness of different metrics between sports, advances in technology, practitioner preferences, and the ever-increasing number of methods used to quantify training load. Additionally, a key consideration for training adolescent athletes is the effect of maturation on the response to training. [12]. However, only four studies reported the maturation levels of their participants, limiting the ability to draw conclusions on the response to training load at different stages of adolescence. Previously, it has been shown that using chronological age as a surrogate for maturation is flawed as adolescent's mature at different rates [201]. Given that maturity status can be assessed with relative ease (e.g. peak height velocity [96]), researchers may wish to consider reporting this data when investigating adolescent populations. This information would help inform future research on the role of maturation in the load-response relationship.

The lack of consistent findings in this review may be due to the multi-factorial nature of the load-response relationship. The individual response to training load is both positively and negatively influenced by factors such as physical qualities [22, 202, 203], stress [204], sleep [205], nutrition [206], and academic stress [207]. For example, one study found that self-esteem, sleep, and nutrition altered the injury rates in adolescent athletes in a multi-sport cohort [180]. It has also been demonstrated that increased stress levels correlate to a reduced adaptation to aerobic training [204]. The heterogeneity of the included studies and the complex nature of any latent relationship may have caused further noise in attempting to establish relationships with training load. The ability to adequately recover from a training dose is inextricably linked to non-training related factors. Therefore, the "Goldilocks" effect should not be viewed as solely being related to load. However, it is not feasible to accurately measure all of the factors that may influence the response to training load. Instead, practitioners may be best served to understand that rapid increases in stress, or prolonged periods of excessive stress, are likely to have negative outcomes and proactively modify loads accordingly.

To address the complex nature of the load-response relationship, it has recently been proposed that advanced statistical methods may be appropriate [208]. Most studies included in this review used logistic and linear regression methodologies, which are bound by fairly stringent assumptions (e.g., normality of residuals, homogeneity of variance) and are susceptible to issues such as multicollinearity [68]. These limitations may be accounted for by using alternative statistical techniques such as dimension reduction or feature selection algorithms. Compared to univariate correlation analysis, statistical methodologies that use dimension reduction (such as principle component analysis) or feature selection algorithms (such as elastic net regressions) may be more appropriate to establish a load-response relationship. By accounting for multi-collinearity these techniques may be less likely to report spurious correlations. These techniques have previously been used to establish the relationship between training load and changes in aerobic fitness in adult athletes [68], as well as for talent identification [209]. Consequently, it is recommended that researchers consider the appropriateness of the statistical technique used when attempting to establish a dose-response relationship.

4.6 Conclusion

This systematic review is the first to investigate and detail the relationships between internal and external methods of monitoring training load and their relationship with changes in physical qualities, injury, or illness in adolescent athletes. The most commonly reported monitoring tools were sRPE and training duration. There was moderate evidence of a relationship between resistance training volume load and strength, and between throw count, training duration, and injury. However, all other relationships were either limited or inconsistent. The lack of consistent or strong relationships with load monitoring tools is likely due to the complex, individualised response to training load. Furthermore, whilst there was a general trend that greater training duration increased injury risk, inconsistencies in the reporting of training duration, and injury definitions, makes drawing conclusions difficult, and there is limited practical application of this finding. There was disproportionate representation of male's within this systematic review, highlighting the need for more research in female athletes. This systematic review's lack of clear trends is potentially due to the univariate nature of the data provided, which fails to account for the complex nature of any relationship between load and training outcomes where numerous mediating factors likely influence the load-response relationship. Therefore, researchers may wish to assess the interactions between multiple training loads through advanced statistical methods and their outcomes and consider mediating factors, such as maturation, that may influence this relationship.

Based on the current evidence, resistance training volume appears to be the best load monitoring tool for improving strength in adolescent athletes. Collecting resistance training volume is highly practical, requires relatively few resources to collect, and is simple to analyse. Throw count and training duration may also be valuable to assess injury risk in sports where they are applicable. Whilst the development of strength should be a key focus of adolescent development [2], this measure is only relevant to resistance training and likely only captures a small portion of the adolescent monitoring puzzle. As such, other methods are needed to quantify training and non-training stressors that are likely to influence training outcomes.

Chapter 5. Study 2 - Training practices of adolescent male Rugby Union players and relationship to change in physical qualities

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Dudley C, Johnston R, Westbrook H, Weakley J. Training practices of adolescent athletes and relationship to change in physical qualities. Journal of Australian Strength and Conditioning (*in press*).

5.1 Introduction

Rugby Union is an intermittent collision-based field sport that requires high levels of strength, power, speed, and skill. Therefore, multiple physical qualities, in addition to rugby specific skills, should be developed [2]. Previous research investigating the training demands of Rugby Union has primarily examined either the field-based training demands of adolescent athletes [23, 32, 56], or has focussed on the resistance training based demands [31]. However, little research has provided a descriptive account of both the field and resistance training demands placed on adolescent schoolboy rugby players. Training load can stimulate positive adaptations, but may also impair performance through fatigue, and therefore needs to be carefully managed. Adaptation is stimulated by the application of adequate stressors, followed by rest, and recovery [18]. However, the stress and recovery process is highly individualised, making it important to assess each athlete's response to the training load.

Previously, research has separately quantified the resistance, and field-based training load of adolescent rugby players. Weakley et al., [31] reported the resistance training practices of adolescent rugby players using player diaries. Players who had the highest upper-body volume load ($r = 0.45 – 0.73$) and recorded greater frequency in upper-body exercises ($r = 0.41 – 0.65$) had greater increases in upper-body strength [31]. Total resistance training frequency ($r = 0.24 – 0.39$) and lower-body volume load ($r = 0.49 – 0.74$) was correlated to increases in measures of jump performance [31]. Further, field based training load was assessed using sRPE, as opposed to GNSS, which whilst practical, offers a less descriptive account of the load performed [31]. Training load data is often used to assess the relationship between training and outcome measures, such as changes in physical qualities. It has previously been proposed that there are high amounts of collinearity in training load monitoring data, which would preclude the use of standard least squares regression techniques [210]. Therefore, investigation of the detailed field, and resistance training loads, and quantifying their relationship to changes in physical qualities, using advanced statistical methods is warranted.

There are many different methods of assessing athletes' levels of readiness. These include objective tools, such as jump performance, and subjective tools, such as questionnaires [62]. Questionnaires have been shown to reflect the acute and chronic training load, and are often practical to implement, as there is minimal interruption to training [175, 211]. One previously validated questionnaire is the Short Recovery and Stress Scale (SRSS) [212]. This questionnaire comprises of eight scales, four of which relate to the level of stress, and four of which rate to the level of recovery. One of the key components of the SRSS is that stress and recovery are assessed separately, and therefore an athlete may have both a high level of stress and a high level of recovery. Therefore, the SRSS may be useful in determining athletes' subjective levels of stress and recovery throughout a training period.

Considering the above the aim of this study was to 1) quantify the training loads, both field and resistance training, in adolescent rugby players 2) quantify the changes in levels of stress and recovery of athletes throughout the pre-season period, 3) assess the degree of multicollinearity in training load data and 4) assess the relationship between training loads and changes in physical qualities in adolescent rugby players.

5.2 Methods

Approach to the problem

The training practices, and subjective levels of stress and recovery of adolescent rugby players were recorded for a period of eight weeks. Height, weight, and maturation were assessed at the start of the observational period. 10m and 40m sprint, IMTP, 2-6RM bench press, and CMJ were assessed pre and post the observational period. Testing sessions were scheduled on days whereby the subjects should have had at least 24 hours rest. However, external training requirements compromised the post-testing session, as five subjects attended representative training the evening prior to post-testing, which sRPE data indicated was over an hour of "hard" training. The eight-week observational period occurred during the pre-season period. Throughout this period, normal training practices and data collection were affected by natural disaster (floods), and the COVID pandemic, with two weeks of data compromised. As such, training load data is expressed as per completed training week.

Subjects

Thirty schoolboy adolescent male rugby players (mean ± SD age: 17.2 ± 0.7 years, height 1.79 ± 0.07 m, maturation 6.5 ± 0.8 age at peak height velocity, body mass 87.0 ± 11.6 kg) were recruited for this study. However, six subjects withdrew due to unrelated reasons. All subjects were recruited from a local high school and were in a pre-season period. Subjects were free from any musculoskeletal injury that would preclude them from any physical activity and had at least six months resistance training experience. Ethics approval was granted by the Australian Catholic University human research ethics committee (2021-217HE). All subjects and parents were provided with an information letter and gave written assent, along with parental consent.

Procedures

Testing procedures were completed across a single testing session. Owing to the large number of subjects and limited facilities and time, testing procedures were completed in a circuit fashion. The three stations completed were a) 40m (10m, 40m split) sprint; b) Bench Press, and CMJ and c) IMTP and anthropometrics. Subjects were instructed to ensure a 2-3 minute rest between testing trials. All subjects then performed the 2km time trial. Post-testing sessions were performed in an identical order to pre-testing. All subjects completed a standardised general warm up. Due to scheduling, the times of the sessions changed, with the pre-testing sessions being conducted in the afternoon (15:00 hrs), and the post-testing session being conducted in the morning (06:00 hrs).

Subject height was recorded using a stadiometer (Design No.1013522, Surgical and Medical Products, Seven Hills, Australia). Subjects removed their shoes and stood facing away from the device and were instructed to keep their head level. Upon inhalation, the researcher adjusted the measuring device until it touched the subjects head and was parallel to the floor. Seated height was measured by the subject sitting on a box, with the height of the box (31cm) then subtracted from the final result. Heights were recorded to the nearest 0.1cm. The standing height and seated height measurements were used to approximate level of maturation using the Mirwald equation [96].

To assess acceleration and speed, subjects completed a 40m linear sprint. Sprint times were measured using single beam timing system (TC Photogate; Brower timing systems, Draper, UT, USA) that has been previously shown to be reliable for both 10m (CV: 2.5%; 90%CI 2.1-3.5) and 40m (CV: 1.8%; 90%CI 1.5 – 2.3) [100] in adolescent athletes. Gates were set up at 0, 10 and 40m splits, with all gates height set at 60cm [101]. A 10m split was used to assess acceleration, and the 40m split was used to assess maximum speed. The test was completed on an outdoor running track. Subjects were instructed to take a 2-point stance 30cm behind the first gate, indicated with a cone, and self-initiated the start of the sprint [102].

Subjects completed the IMTP on a force plate (ForceDecks, Vald, Brisbane, Australia), sampling at 1000Hz. Bar height was adjusted to obtain knee and hip angles of 125 – 145° and 140 - 150°, respectively [37]. Subjects were instructed to maintain an upright torso, with shoulders slightly retracted and depressed [37]. Subjects used an overhand grip, with figure eight lifting straps (Loaded Lifting, Perth, Australia) to ensure a firm grip on the bar [37]. To begin, subjects took the slack out of the bar, and the live force-time trace was visually inspected to ensure a stable baseline. Subjects were given an audible countdown – "On go, pull as hard and fast as possible. 3, 2, 1, GO! Pull, Pull, Pull". Subjects completed warm up trials of 3 x 3 seconds at 50%, 75% and 90% perceived effort [37]. Subjects were afforded two trials, with the trial with the greatest peak force was used for analysis.

The bench press was performed on a standard gym bench. The subject took the bar out of the rack, lowered it to their chest, before driving the bar to full lockout without assistance. A spotter was used for all working sets. Subjects completed warm up sets of eight repetitions, two sets of five repetitions and one set of three repetitions at self-selected loads [31]. Subjects were then instructed to increase the load and complete one set of maximal repetitions. The load and repetitions performed on the maximal set was manually recorded. Estimated 1RM was calculated using the Baechle Formula [213]. If subjects achieved greater than six repetitions or did not complete a single repetition on their test set, the load was adjusted, and a second test set was performed.

The CMJ was completed on a force platform (ForceDecks, Vald, Brisbane, Australia), sampling at a rate of 1000 HZ. Subjects were instructed to stand on the platform with the hands on their hips, and feet approximately shoulder width apart. Instructions to subjects were "On go, jump as high as possible. 3, 2, 1 GO!" . All jumps were performed to a self-selected depth. Data from countermovement jumps were uploaded to a cloud-based platform (ValdHUB, Vald, Brisbane, Australia), with performance results downloaded to CSV for analysis.

Throughout the observational period, resistance, field-based, and external training load was collected. External training load was any structured training that took place outside of the scheduled sessions, for example, representative or club training. For resistance training sessions, players self-reported their training practices using Teambuildr (Teambuildr LLC, Maryland, United States of America). Following each training session subjects self-reported the exercise, sets, repetitions, and load of each exercise. Upper body, lower body, full body and trunk volume (sets × repetition), volume load (sets × repetitions x load) were collected. However, for some exercises, repetitions could not be calculated (i.e., sled push, isometric holds) and therefore repetition volume was only reported as number of sets for these exercises. Additionally, volume of "Sports specific skills" (SSS) was recorded. For example, traditional gym exercises, such as a squat, were often performed in a superset with a low intensity skill exercise, such as a passing drill.

For field-based training, subjects training volume was recorded using both GNSS (Optimeye S5 or Catapult X4, Catapult Sports, VIC, Australia) and sRPE CR-10 [106]. For external training activities, subjects training volume was recorded using sRPE [106]. Subjects completed the sRPE questionnaires through Teambuildr approximately 15 minutes following each training session. sRPE questionnaires were completed independently and blinded from other subjects to control for peer influence [106]. To collect GNSS data, devices were secured to subjects thoracic region using fitted bibs. Data was collected and transmitted to an online cloud-based platform, before being downloaded to custom-built spreadsheets (Microsoft Excel 2016, Microsoft Corporation, Redmond, USA). Variables that were analysed were total distance (m), Acceleration load (AU), PlayerLoad (AU), Walking (<3 m.s-1), Jogging (3 – 5 m.s-1), Running (5 – 7 m.s-1), Sprinting (>7 m.s-1), which have been shown to be reliable [104]. Drills were categorized into being either tactical, technical, conditioning, warm up, or SSG (Table 5.1).

Table 5.1. Drill categorisation

Activity	Definition
Tactical	Primary focus of the activity is the development of a "Tactic"
Technical	Primary focus of the activity is the development of a sport specific skill
Conditioning	Primary focus of the activity is the development of physical qualities
SSG	The activity is a game-based variation of Rugby, designed to simultaneously target tactical, technical and conditioning.
Warm up	Primary focus of the activity is preparedness for the main training session.

To assess changes in subjective levels of stress and recovery, subjects completed a short recovery and stress questionnaire at the start of each week, prior to any training activity. At the beginning of the observational period the component questions of the SRSS were explained to subjects. The SRSS was delivered via TeamBuildr, with data downloaded to .csv for analysis.

Statistical analysis

Data were assessed for normality and were presented as mean ± SDs. Effect sizes ± 95%CI were calculated for change in physical qualities. Due to the small sample size, Hedges g statistic was computed to avoid the positive bias associated with Cohen's *d [214]*. Data were assessed, and plots created, using the R statistical programming language (R version 4.2.1, R Foundation for Statistical Computing, Vienna, Austria) within the RStudio environment (Version 1.1.383, Posit, Boston, MA). Packages used for analysis were *dplyr, caret, glmnet, tidyverse, ggplot2* and *varhandle.*

Preliminary assessment of the collinearity of the training load data was performed using Pearson correlation analysis. Correlations were considered trivial (r = 0 – 0.09), small (r = 0.10 – 0.29). moderate (r = 0.30 – 0.49), large (r = 0.5 – 0.69), very large (r = 0.70 – 0.89), nearly perfect (r = 0.90 – 0.99) and perfect (r = 1.00) [214]. Following this, VIF were calculated for predictor variables, with scores > 10 being identified as indicating collinearity [68]. To assess VIF, a linear regression model was initially performed, using all training load variables as independent variables, and a dummy variable as the dependant variable. Then, aliased coefficients were removed, and the model was passed into the *VIF* function.

Given the high degree of multicollinearity in the dataset, elastic net regression was employed to assess the relationships between training load and changes in physical qualities. Elastic net regression combines both Lasso and Ridge regularisation techniques [71], to balance under and over-fitting of the regression model through tuning the two hyperparameters, alpha and lambda. This results in some coefficients being shrunk to zero or close to zero to control multicollinearity and create a parsimonious final model. Therefore, the assumption of multi-collinearity does not need to be met. The elastic net model was trained using repeated cross-validation with 10 folds, repeated five times. *K*-fold cross-validation involves splitting the dataset into *k* equal folds where each the model is trained on *k*-1 fold and tested on the k^{th} fold. This process is repeated until each fold has been used for both training and testing. A grid search technique was used to set alpha and lambda values. Results from the elastic net regression were then passed into the *VarImp* function, to assess the variables of importance for the relative models, with variables of importance > 10 presented. The coefficient of determination (R^2), normalised root mean square error (NRMSE) and mean absolute error for each model were used to represent model performance.

5.3 Results

5.3.1 Overall training load distribution

Table 5.2 presents the mean weekly training loads (i.e., number of sessions, duration, and load) of all training, resistance based training, field training and external training sessions (n = 25), for periods of uninterrupted data collection. The distribution of training load, expressed as a percentage of overall training load is illustrated in Figure 5.1.

Table 5.2 Mean weekly training loads

	Total	Resistance training	Field sessions	External Training
Number of sessions	5.60 ± 1.60	2.45 ± 0.34	2.73 ± 0.54	0.46 ± 0.05
Training time (Minutes)	394 ± 101.2	144.7 ± 20.27	219.5 ± 44.60	28.20 ± 2.90
Training load (AU)	2060 ± 526.2	702 ± 206.90	1156 ± 382.4	125.96 ± 11.70

Data are mean ± SD; AU = Arbitrary Units.

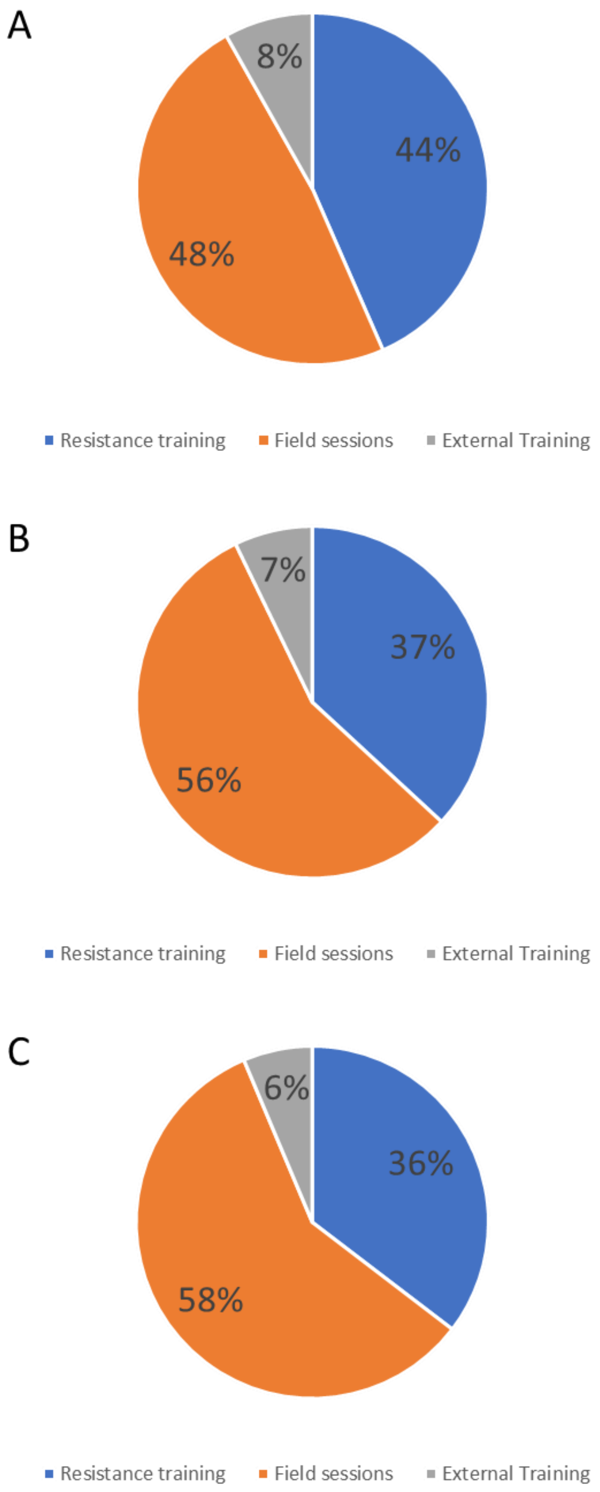


Figure 5.1. Distribution of training loads for A) Number of sessions, B) Training time, and C) Training load.

5.3.2 Description of resistance training loads

Table 5.3 presents the mean weekly resistance training loads.

Table 5.3. Mean weekly resistance training loads

Load metric	Mean weekly load
Number of sets	67.0 ± 7.5
Number of exercises	18.6 ± 2.1
Total number of repetitions	507.1 ± 60
Upper body number of exercises	5.6 ± 0.6
Upper body number of sets	19.9 ± 2.1
Upper body number of repetitions	218.3 ± 22.4
Lower body number of exercises	5.7 ± 0.9
Lower body number of sets	20.3 ± 3.4
Lower body number of repetitions	131.3 ± 22.8
Full body number of exercises	2.6 ± 0.4
Full body number of sets	10.0 ± 1.5
Full body number of repetitions	34.5 ± 7.7
Trunk number of exercises	3.3 ± 0.3
Trunk number of sets	12.1 ± 1.3
Trunk number of repetitions	122.0 ± 21
SSS number of exercises	1.4 ± 0.2
SSS number of sets	4.8 ± 0.6

Data are mean ± SD; SSS = Sports Specific Skills.

5.3.3 Description of field based training loads

Table 5.4 presents the mean weekly distances (Total, walking, jogging, running and sprinting), acceleration load, and PlayerLoad. The distribution of field-based training loads between tactical, technical, conditioning, SSG and warm-up activities is presented in Figure 5.2. Additionally, the distribution of walking, jogging, running and sprinting for each activity type is presented in Figure 5.3. Table 5.5 presents the distribution of average metres per minute and acceleration density for each activity type.

Table 5.4. Mean weekly field-based training loads

Training metric	Mean weekly load
Total distance (m)	13118 ± 3085
Acceleration load (AU)	4114 ± 834
PlayerLoad (AU)	1329 ± 285
Walking (<3 $m.s^{-1}$)	9863 ± 2119
Jogging (3 – 5 $m.s^{-1}$)	1767 ± 537
Running (5 – 7 $m.s^{-1}$)	1417 ± 494
Sprinting (>7 $m.s^{-1}$)	66 ± 41

Data are mean ± SD. AU = arbitrary units.

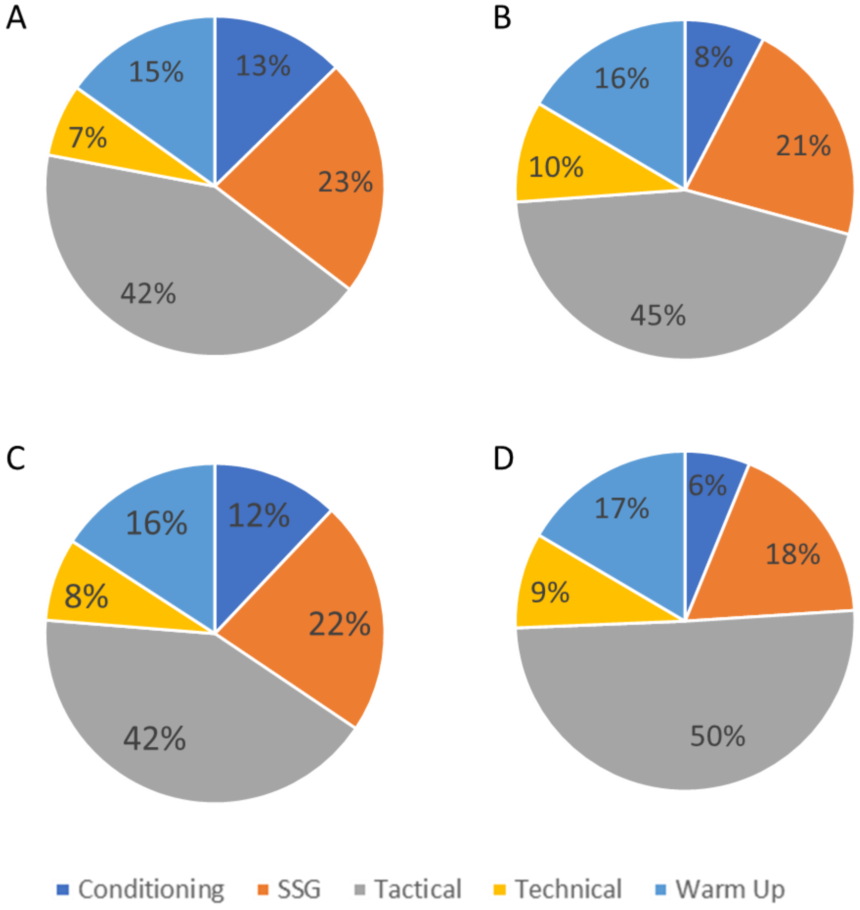


Figure 5.2. Distribution of training load for A) Total distance, B) Acceleration load, C) PlayerLoad and D) Duration.

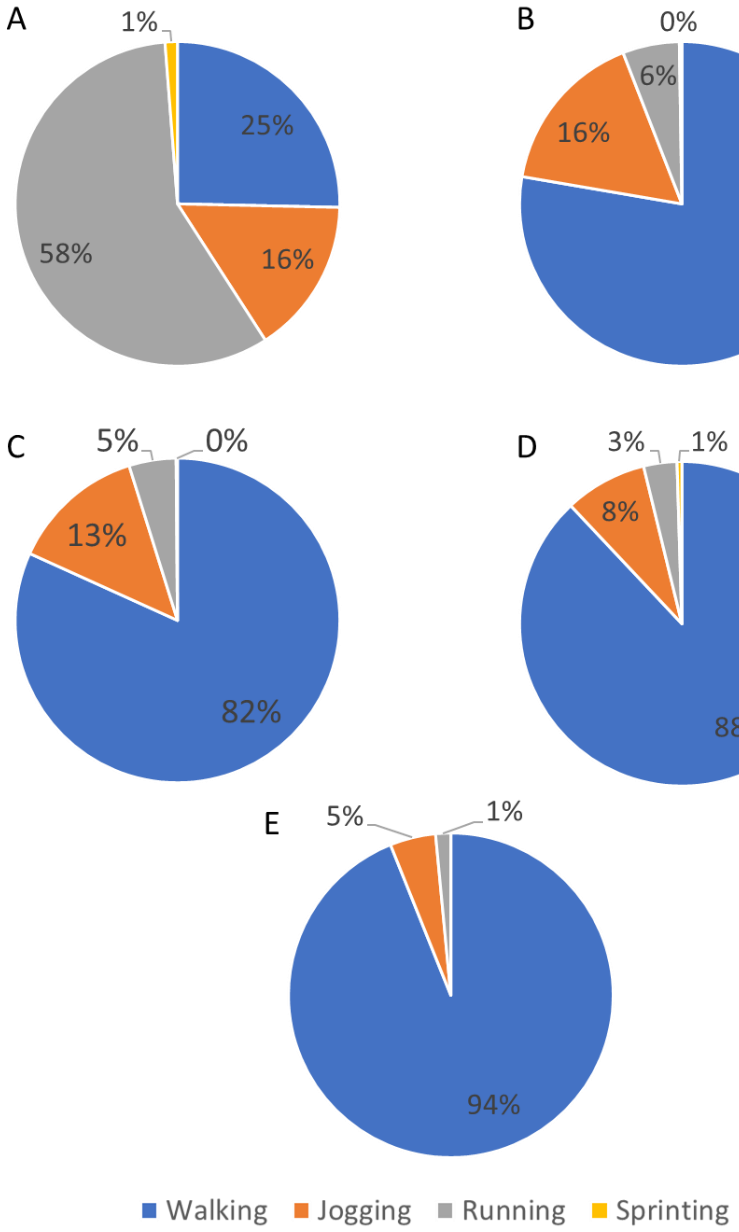


Figure 5.3. Distribution of distance in running bands for A) Conditioning, B) SSG, C) Tactical activities, D) Technical activities and E) Warm ups.

Table 5.5. Average intensities for different activity classifications

	Metres per minute	Acceleration Density
Conditioning	145.2 ± 47.8	0.45 ± 0.13
Game based drills	89.0 ± 30.7	0.46 ± 0.13
Tactical	55.3 ± 25.3	0.30 ± 0.11
Technical	45.7 ± 16.1	0.33 ± 0.11
Warm up	54.4 ± 11.8	0.31 ± 0.08

Data are mean ± SD.

5.3.4 Short Recovery and stress scale

The short recovery and stress survey was completed with an 89.9% response rate throughout the observational period. There were no significant changes in levels of stress (Figure 5.4) or levels of recovery (Figure 5.5) throughout the observational period.

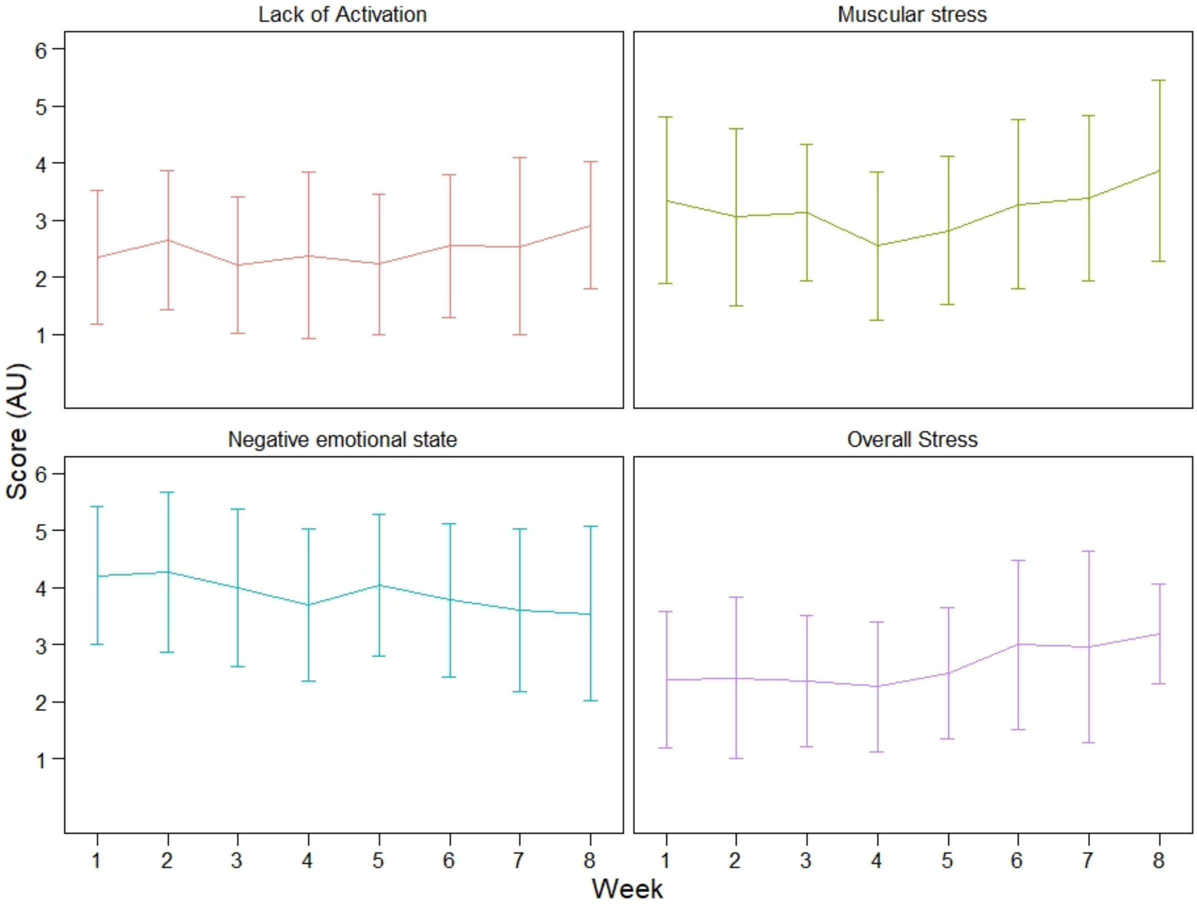


Figure 5.4. Changes in levels of stress throughout the observational period. Data are mean ± SD ;.

AU = Arbitrary units.

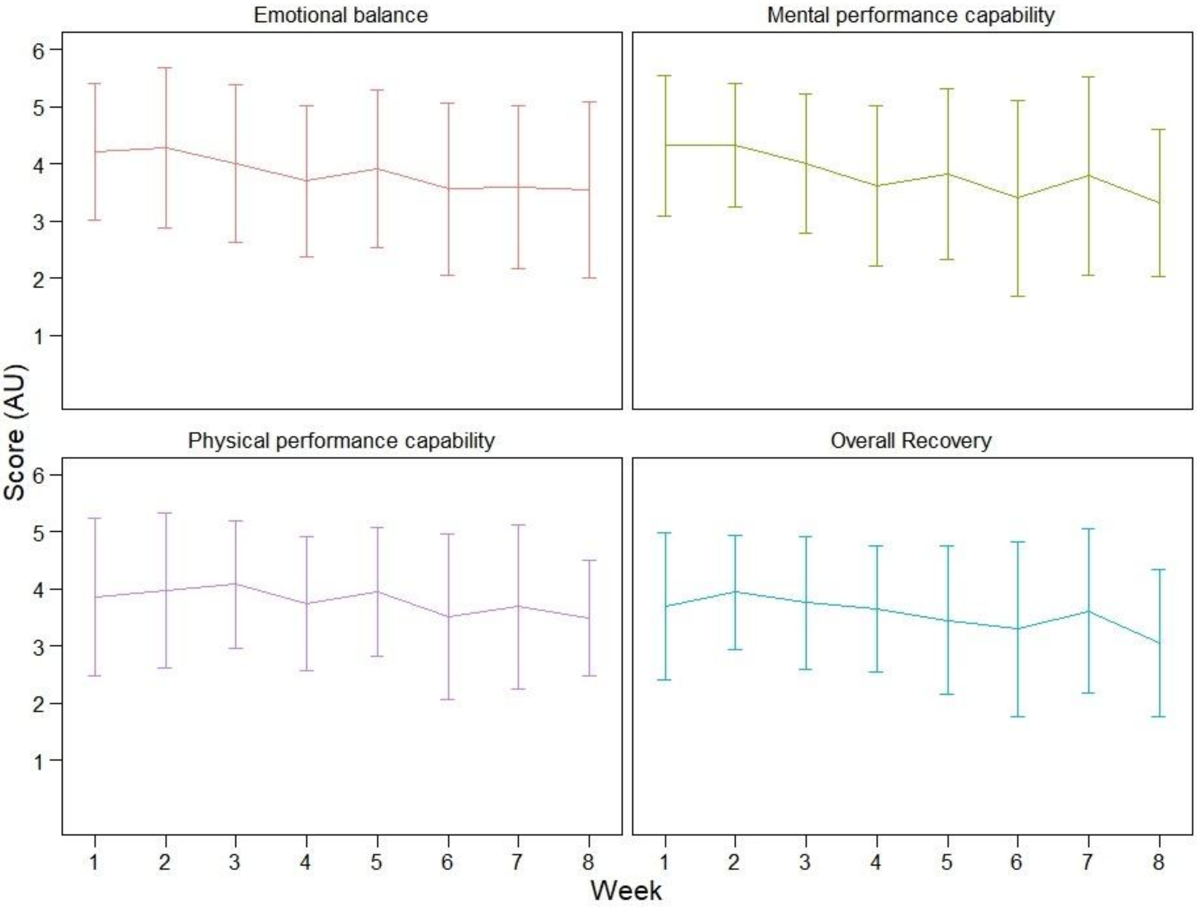


Figure 5.5. Changes in levels of recovery throughout the observational period. Data are mean ± SD ;. AU = Arbitrary units.

5.3.5 Changes in physical characteristics

Changes in physical characteristics are presented in Table 5.6

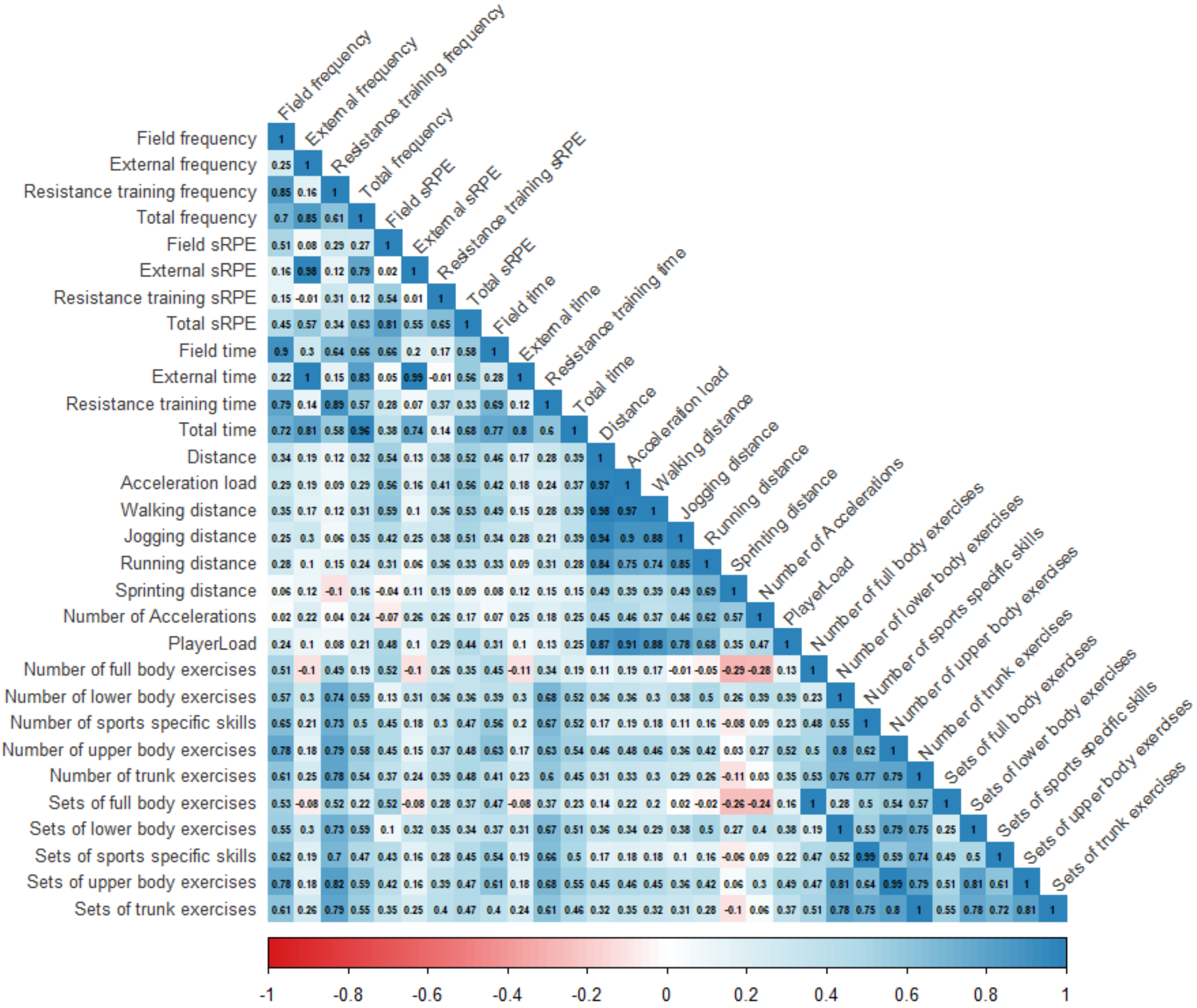
Table 5.6. Strength, speed, and countermovement jump characteristics of adolescent rugby players before and after the 8-week observational period.

	Pre	**Post**	**p-value**	**Effect Size (90%CI)**	**n**
Bench Press 1RM (kg)	102.49 ± 13.83	106.23 ± 14.30	0.02;	0.26 (-0.29, 0.81); Unclear	18
IMTP Peak force (N)	3369 ± 550	3586 ± 570	<0.01;	0.38 (-0.20, 0.96); Unclear	18
10m time (s)	1.77 ± 0.06	1.77 ± 0.08	0.73;	0.01 (-0.60, 0.60); Unclear	15
40m time (s)	5.37 ± 0.17	5.35 ± 0.14	0.16	-0.12 (-0.73, 0.48); Unclear	15
CMJ Jump height (cm)	34.78 ± 3.47	34.94 ± 3.70	0.78	0.04 (-0.66, 0.74); Unclear	11
2km run time	7min 59s ± 49s	7min 46s ± 47s	<0.01	-0.26 (-0.83, 0.30); Unclear	17

Data are Mean ± S.D. 1RM = One repetition maximum; IMTP = Isometric midthigh pull; CMJ = Countermovement Jump; km = Kilometre.

5.3.6 Multi-collinearity in training load data

Pearson correlation analysis of the 569 relationships between training load variables revealed 3.9% had nearly perfect correlations, 11.1% had very large correlations, 20.7% had large correlations, 29.2% had moderate correlations, 26.7% had small correlations and 8.4% had trivial correlations (Figure 5.6). All VIF values were greater than 10.



	Field frequency	External frequency	Resistance training frequency	Total frequency	Field sRPE	External sRPE	Resistance training sRPE	Total sRPE	Field time	External time	Resistance training time	Total time	Distance	Acceleration load	Walking distance	Jogging distance	Running distance	Sprinting distance	Number of Accelerations	PlayerLoad	Number of full body exercises	Number of lower body exercises	Number of sports specific skills	Number of upper body exercises	Number of trunk exercises	Sets of full body exercises	Sets of lower body exercises	Sets of sports specific skills	Sets of upper body exercises	Sets of trunk exercises
Field frequency	1																													
External frequency	0.25	1																												
Resistance training frequency	0.85	0.16	1																											
Total frequency	0.7	0.85	0.61	1																										
Field sRPE	0.51	0.08	0.29	0.27	1																									
External sRPE	0.16	0.98	0.12	0.79	0.02	1																								
Resistance training sRPE	0.15	-0.01	0.31	0.12	0.54	0.01	1																							
Total sRPE	0.45	0.57	0.34	0.63	0.81	0.55	0.65	1																						
Field time	0.9	0.3	0.64	0.66	0.66	0.2	0.17	0.58	1																					
External time	0.22	1	0.15	0.83	0.05	0.99	-0.01	0.56	0.28	1																				
Resistance training time	0.79	0.14	0.89	0.57	0.28	0.07	0.37	0.33	0.69	0.12	1																			
Total time	0.72	0.81	0.58	0.96	0.38	0.74	0.14	0.68	0.77	0.8	0.6	1																		
Distance	0.34	0.19	0.12	0.32	0.54	0.13	0.38	0.52	0.46	0.17	0.28	0.39	1																	
Acceleration load	0.29	0.19	0.09	0.29	0.56	0.16	0.41	0.56	0.42	0.18	0.24	0.37	0.97	1																
Walking distance	0.35	0.17	0.12	0.31	0.59	0.1	0.36	0.53	0.49	0.15	0.28	0.39	0.98	0.97	1															
Jogging distance	0.25	0.3	0.06	0.35	0.42	0.25	0.38	0.51	0.34	0.28	0.21	0.39	0.94	0.9	0.88	1														
Running distance	0.28	0.1	0.15	0.24	0.31	0.06	0.36	0.33	0.33	0.09	0.31	0.28	0.84	0.75	0.74	0.85	1													
Sprinting distance	0.06	0.12	-0.1	0.16	-0.04	0.11	0.19	0.09	0.08	0.12	0.15	0.15	0.49	0.39	0.39	0.49	0.69	1												
Number of Accelerations	0.02	0.22	0.04	0.24	-0.07	0.26	0.26	0.17	0.07	0.25	0.18	0.25	0.45	0.46	0.37	0.46	0.62	0.57	1											
PlayerLoad	0.24	0.1	0.08	0.21	0.48	0.1	0.29	0.44	0.31	0.1	0.13	0.25	0.87	0.91	0.88	0.78	0.68	0.35	0.47	1										
Number of full body exercises	0.51	-0.1	0.49	0.19	0.52	-0.1	0.26	0.35	0.45	-0.11	0.34	0.19	0.11	0.19	0.17	-0.01	-0.05	-0.29	-0.28	0.13	1									
Number of lower body exercises	0.57	0.3	0.74	0.59	0.13	0.31	0.36	0.36	0.39	0.3	0.68	0.52	0.36	0.36	0.3	0.38	0.5	0.26	0.39	0.39	0.23	1								
Number of sports specific skills	0.65	0.21	0.73	0.5	0.45	0.18	0.3	0.47	0.56	0.2	0.67	0.52	0.17	0.19	0.18	0.11	0.16	-0.08	0.09	0.23	0.48	0.55	1							
Number of upper body exercises	0.78	0.18	0.79	0.58	0.45	0.15	0.37	0.48	0.63	0.17	0.63	0.54	0.46	0.48	0.46	0.36	0.42	0.03	0.27	0.52	0.5	0.8	0.62	1						
Number of trunk exercises	0.61	0.25	0.78	0.54	0.37	0.24	0.39	0.48	0.41	0.23	0.6	0.45	0.31	0.33	0.3	0.29	0.26	-0.11	0.03	0.35	0.53	0.76	0.77	0.79	1					
Sets of full body exercises	0.53	-0.08	0.52	0.22	0.52	-0.08	0.28	0.37	0.47	-0.08	0.37	0.23	0.14	0.22	0.2	0.02	-0.02	-0.26	-0.24	0.16	1	0.28	0.5	0.54	0.57	1				
Sets of lower body exercises	0.55	0.3	0.73	0.59	0.1	0.32	0.35	0.34	0.37	0.31	0.67	0.51	0.36	0.34	0.29	0.38	0.5	0.27	0.4	0.38	0.19	1	0.53	0.79	0.75	0.25	1			
Sets of sports specific skills	0.62	0.19	0.7	0.47	0.43	0.16	0.28	0.45	0.54	0.19	0.66	0.5	0.17	0.18	0.18	0.1	0.16	-0.06	0.09	0.22	0.47	0.52	0.99	0.59	0.74	0.49	0.5	1		
Sets of upper body exercises	0.78	0.18	0.82	0.59	0.42	0.16	0.39	0.47	0.61	0.18	0.68	0.55	0.45	0.46	0.45	0.36	0.42	0.06	0.3	0.49	0.47	0.81	0.64	0.99	0.79	0.51	0.81	0.61	1	
Sets of trunk exercises	0.61	0.26	0.79	0.55	0.35	0.25	0.4	0.47	0.4	0.24	0.61	0.46	0.32	0.35	0.32	0.31	0.28	-0.1	0.06	0.37	0.51	0.78	0.75	0.8	1	0.55	0.78	0.72	0.81	1

Figure 5.6. Correlation matrix demonstrating the high amount of multicollinearity within the data set.

Table 5.7. Results of the Elastic Net Regression Models for percentage change in physical qualities

	NRMSE	R^2	MAE
Bench Press 1RM (kg)	5.25	0.46	5.10
2km time	3.35	0.60	2.34
10m time	4.04	0.46	2.85
40m time	1.15	0.50	1.04
CMJ Height (cm)	5.25	0.28	4.86
IMTP Peak Force (N)	19.14	0.60	10.85

NRMSE = Normalised root mean squared error, MAE = Mean absolute error, 1RM = 1 repetition maximum

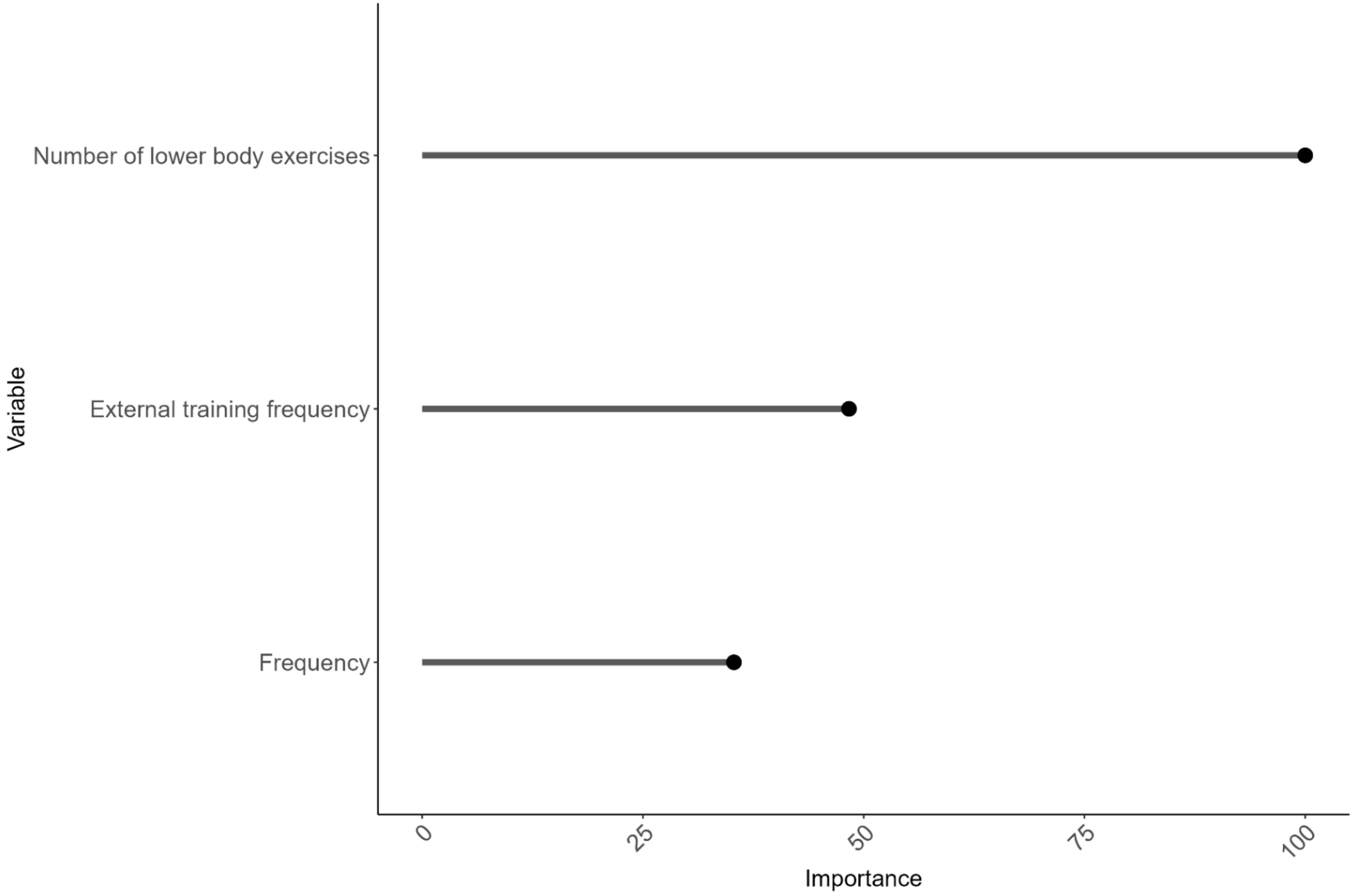


Figure 5.7. Variables of importance for Elastic net regression for percentage increase in Bench Press 1RM.

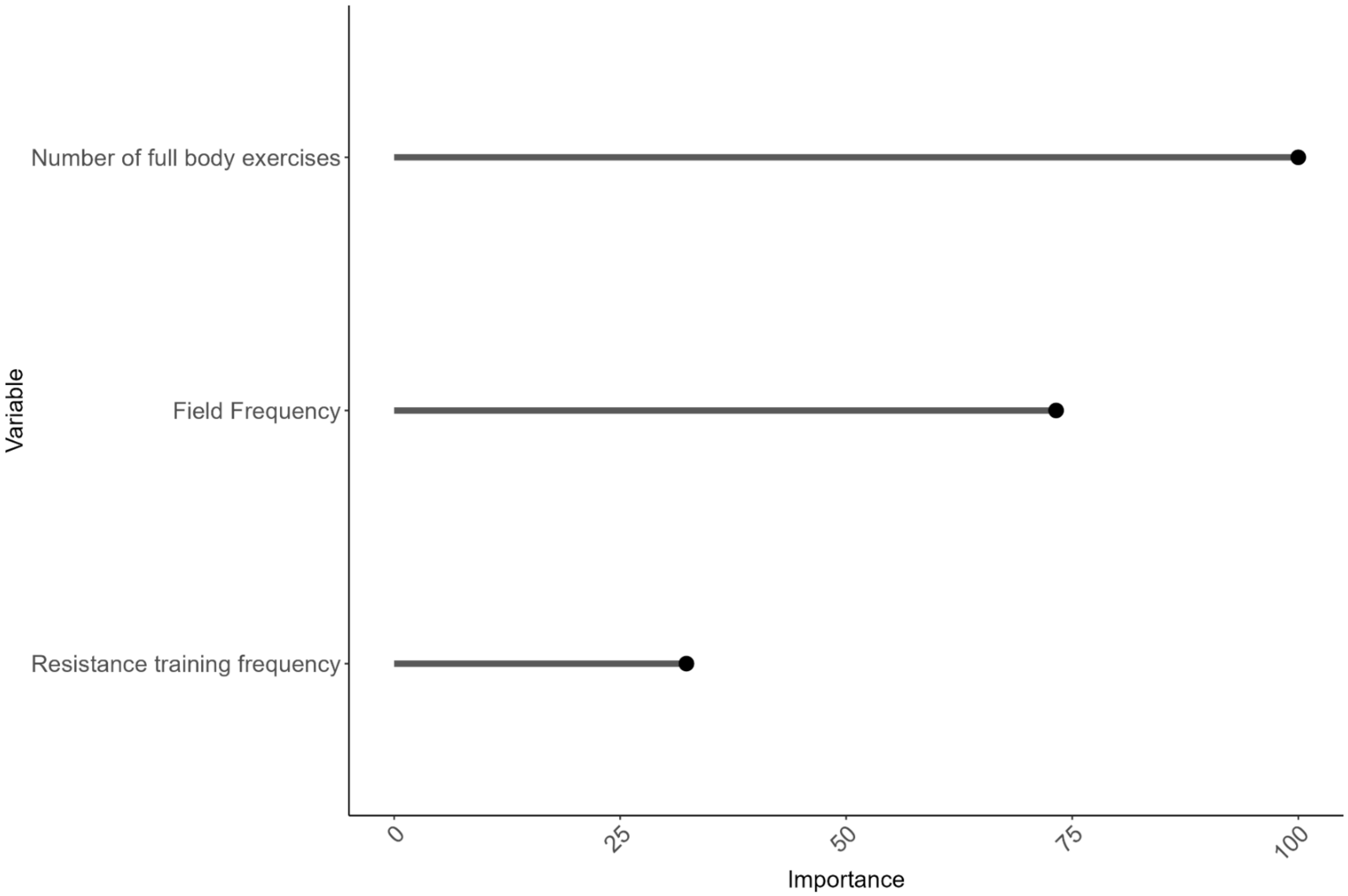


Figure 5.8. Variables of importance for Elastic net regression for percentage increase in CMJ height

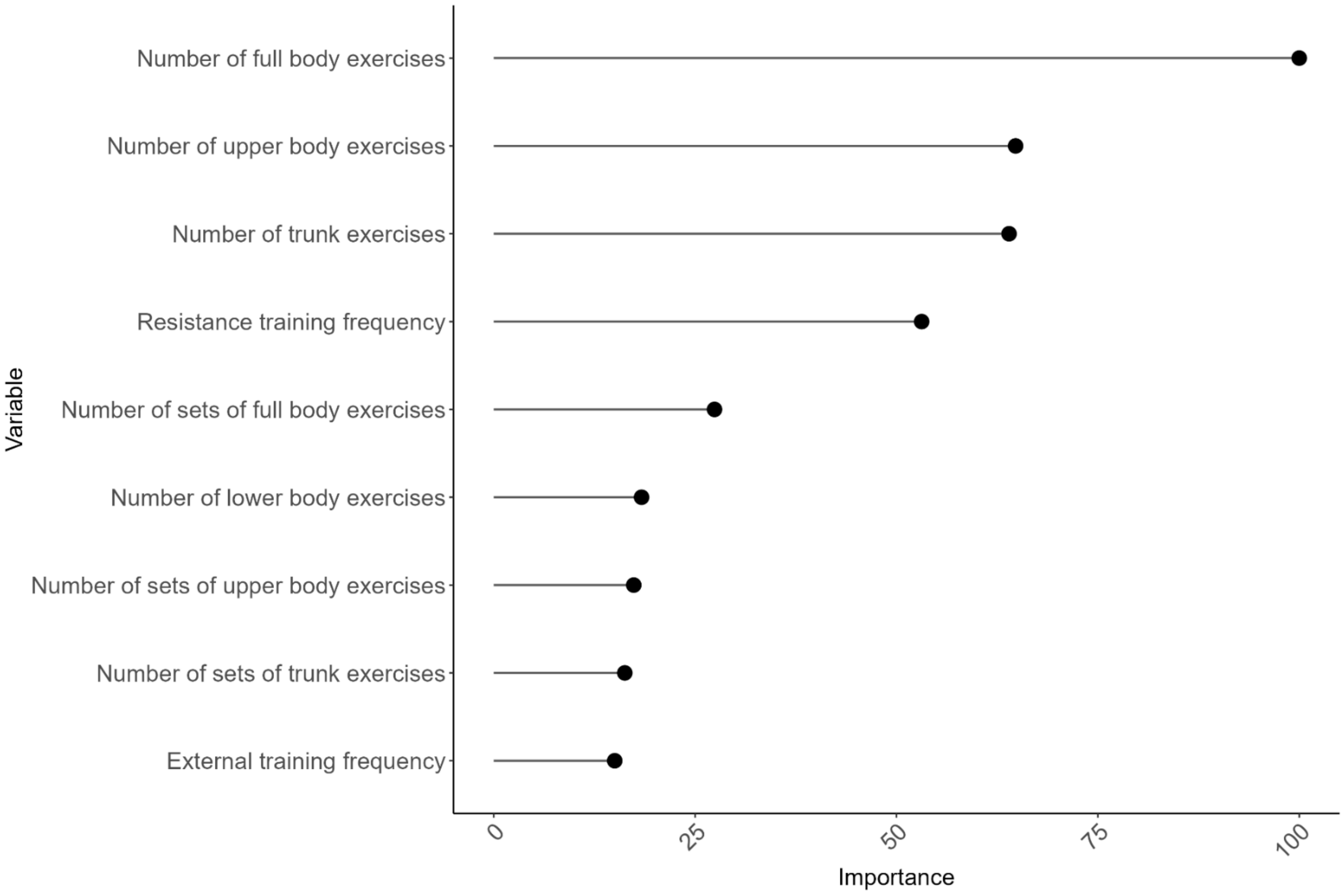


Figure 5.9. Variables of importance for Elastic net regression for percentage increase in isometric mid-thigh pull peak force.

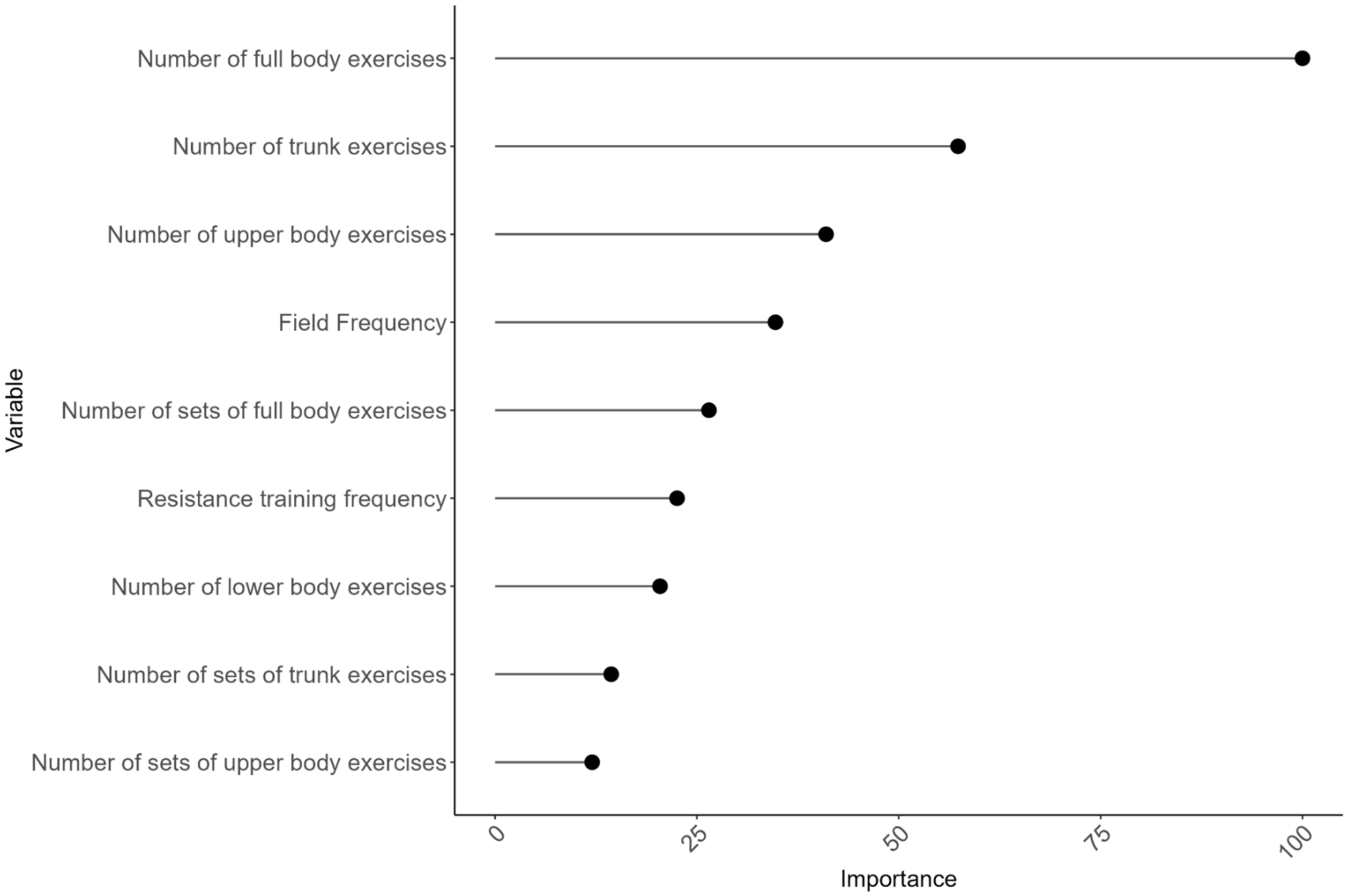


Figure 5.10. Variables of importance for Elastic net regression for percentage increase in 2km run time.

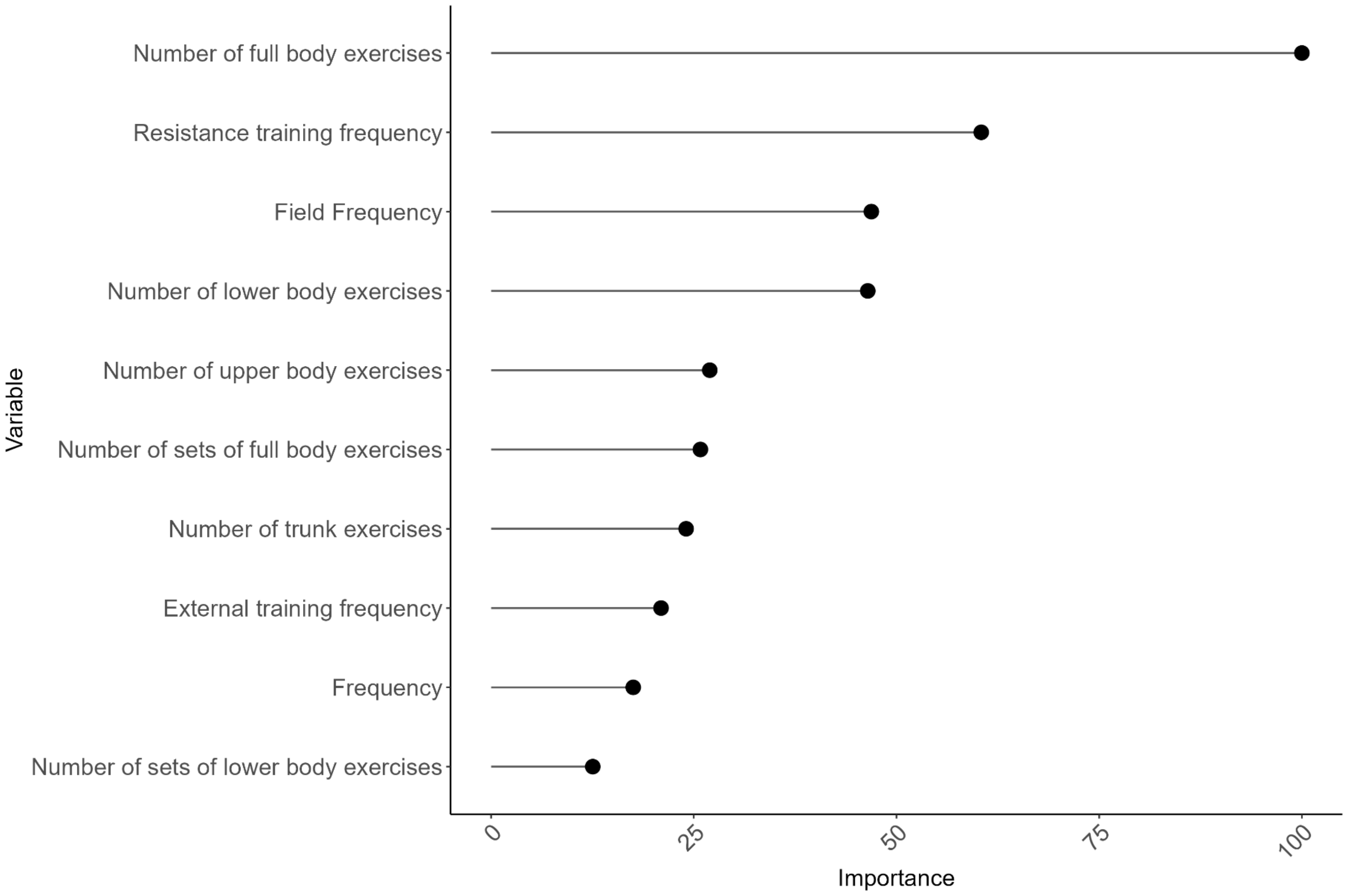


Figure 5.11. Variables of importance for Elastic net regression for percentage increase in 10m run time.

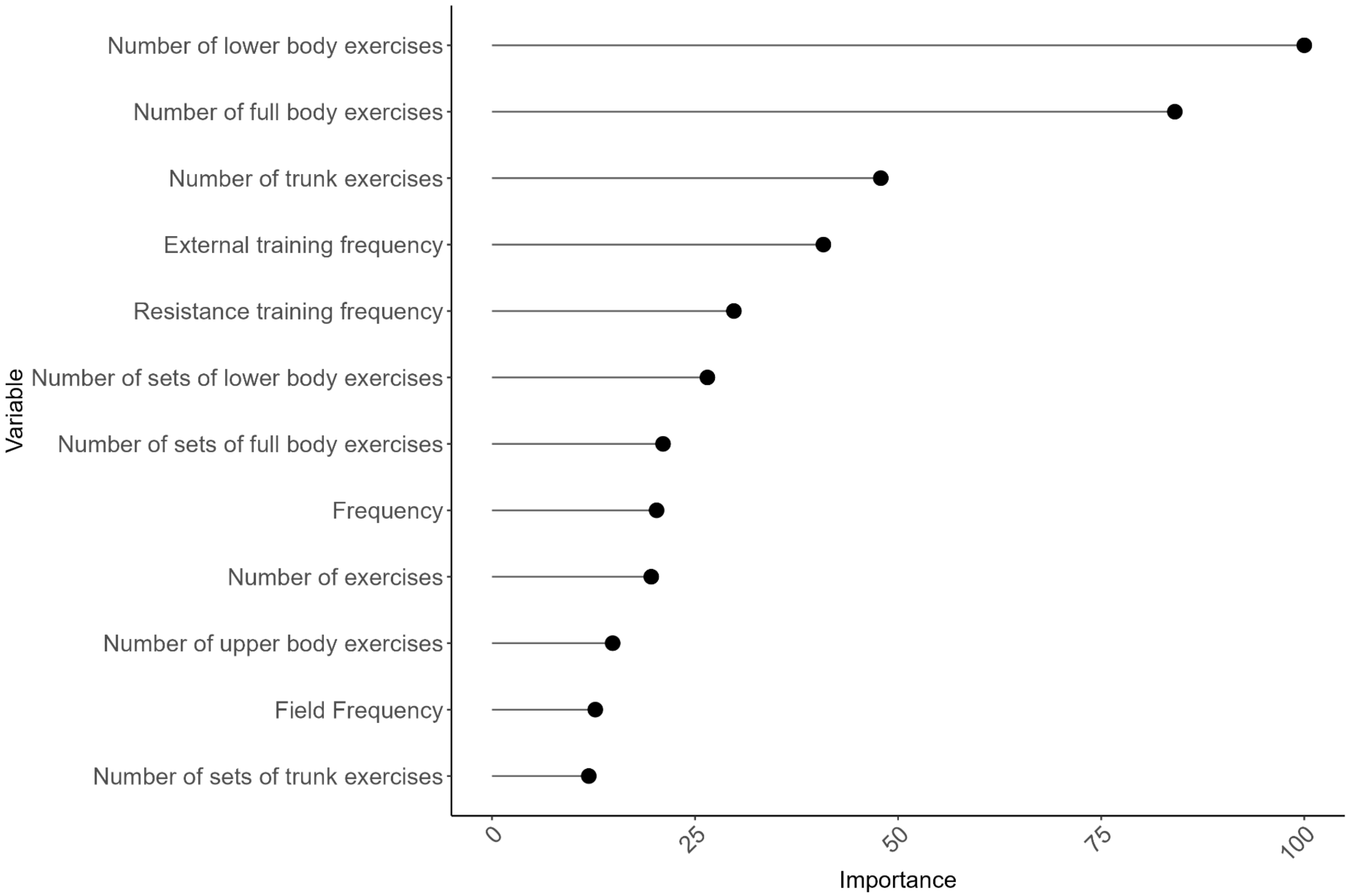


Figure 5.12. Variables of importance for Elastic net regression for percentage increase in 40m run time.

5.4 Discussion

The aim of this study was to 1) quantify the training loads, both field and resistance training, in adolescent rugby players, 2) quantify the changes in levels of stress and recovery of athletes throughout the pre-season period, 3) assess the degree of multicollinearity in training load data, and 4) assess the relationship between training loads and changes in physical qualities in adolescent rugby players over an 8-week in-season period. Findings demonstrated that there was high variability in the training practices and levels of subjective stress and recovery of adolescent rugby players. Further, the weekly training loads in this study were greater than those previously reported in both academy (1217 ± 364 AU) and schoolboy Rugby Union players (1014 AU; range = 195 to 4888) [31, 32]. There were significant improvements in levels of strength and aerobic fitness, however, jump height and speed remained unchanged. Training load data showed high degrees of multicollinearity, therefore, relationships between training load and changes in physical qualities were assessed using elastic net regression models. The number of full body resistance exercises was consistently one of the most important variables across all assessments of physical qualities.

The high loads completed by subjects in this study, as compared to previous research, is likely due to increased total resistance training time, as the field-based training time was similar. The 2.45 ± 0.34 resistance training sessions per week adheres to the 2-3 sessions recommended to be optimal for adolescent athletes [33]. The strength levels of the cohort in this study (as measured by the bench press 1RM) were greater than those previously reported in both academy (3RM = 82.6 ± 10.8 kg) and schoolboy age grade Rugby Union (3RM = 68.5 ± 12.8) players in England [215], but weaker than professional Rugby Union players (mean 1RM range = 111 – 136kg) [216]. Set distribution during the resistance training sessions was split between upper body (30%), lower body (30%), full body (15%), trunk (18%) and sports specific skill based (7%) exercises. This is the first study to report the incorporation of sports specific skill exercises within resistance training sessions. The results of this study, combined with that of previous research, demonstrate that the resistance training loads of adolescent athletes are highly variable across different training studies. Further, the incorporation of skill-based exercises did not appear to negatively affect training outcomes, and therefore should be considered by coaches.

Subjects in this study completed 219 ± 44 minutes of field-based training per week. Whilst the time spent training was similar to time previously reported in academy adolescent Rugby Union players (214 ± 64 minutes) [56], the average total distance per week (13118m) was greater than loads previously described (range = 2672 - 11629m) [215]. However, previous studies were conducted in-season and did report total distance excluding match play, which may have caused under-reporting of total weekly distances [215]. Additionally, this is the first study to report the split of field-based training time between tactical, technical, conditioning, warm up and game-based activities. It was found that the majority of training was tactical based, including training in position specific groups, and development of gameplay tactics. The next greatest contributor to total distance was games-based activities, including SSG, such as touch rugby and match-play based drills. Further, games-based activities had the greatest acceleration density of any drill type. Although no guidelines exist for the distribution of training drills in Rugby Union, the inclusion of a significant amount of games-based drills will likely positively contribute to the long-term development of Rugby players, as they simultaneously train the tactical, technical, physical and psychological demands of the game [42].

This is the first study to report the subjective levels of stress and recovery across a pre-season period in adolescent Rugby Union players using the short recovery and stress scale. No significant changes in any subjective stress or recovery subscales were seen throughout the observational period. However, this is likely due to the high levels of individual variability increasing the noise in group-based data [217]. Given this, coaches should ensure that they examine individualised wellness data as opposed to group-based data.

This study used feature selection algorithms to assess the relationship between changes in physical qualities and training load. Previously, it has been proposed that training load data had high degrees of multicollinearity, and therefore logistic and linear regression methods were inappropriate [210]. All training load variables in this study had VIF values >10, indicating a high degree of multicollinearity. Elastic net regression models were chosen over other more common advanced statistical methods (e.g., principal component analysis) due to the ease of interpretation, as the results for the variables can be assessed individually, as opposed to the creation of principal components, which can be difficult to understand and practically apply. The results of the elastic net regression found *small* to *large* relationships between the changes in physical qualities and training load variables. However, the relatively small sample size, and disrupted training schedule may have influenced these results. Coaches and sports scientists should consider using feature selection algorithms to assess relationships between training load variables and changes in physical qualities.

There are limitations to this study that may influence the applicability of the results, due to the applied, observational nature of the research. First, the training period occurred throughout both a natural disaster and a global pandemic. The natural disaster caused up to two weeks of data to be compromised for subjects. Second, the timing for the pre- and post-testing sessions changed from evening (3.30PM) to morning (6.00AM) due to changes in the training schedule that occurred due to reasons outside of the control of the coaching staff. Third, five subjects were invited to a representative training session that occurred the night prior to post-testing. Therefore, these subjects' data were excluded from final analysis.

5.5 Conclusion

This study presents the training loads, physical qualities, subjective levels of stress and recovery, and changes in training load in adolescent Rugby Union players. The findings have demonstrated that schoolboy Rugby Union players may complete greater resistance training loads, and have higher strength levels, than have been previously reported. Further, the training practices were highly variable between individuals. During field-based training, conditioning drills had the greatest running intensity, whereas SSG had the greatest acceleration density. As previously suggested, high degrees of multicollinearity existed in the training load data. Therefore, a novel method of assessing the relationship between training load and changes in physical qualities using feature selection algorithms was demonstrated.

5.6 Practical applications

The results of this study are useful for both tactical and strength and conditioning coaches of adolescent Rugby Union players. This study demonstrated higher resistance training frequency and greater levels of strength than previously reported. Coaches should therefore ensure adolescent athletes are completing 2-3 resistance training sessions per week. Further, coaches should prescribe full body exercises, as these had the greatest importance when assessing changes in physical qualities. Examples of full body exercises include Olympic weightlifting variations such as hang power cleans.

This is the first study to report incorporating sports-specific skills into resistance training sessions, with no negative effect on resistance training outcomes apparent. Therefore, coaches are encouraged to integrate sports skills into resistance training sessions, to increase skill exposures. Coaches may use a typical superset structure to combine strength exercises, for example a front squat, with a sports-specific skill, such as a static passing drill. This will allow for full recovery from the strength exercise, whilst increasing technical exposures. However, it is important for strength and conditioning coaches to ensure the sports-specific drill has low physical load, to avoid any interference with recovery for the primary strength exercise. Further, the coach must appraise whether the incorporation of a skill drill is practical in their environment, without compromising the strength exercises, considering factors such as the logistics of the training space and the maturity of the athletes.

The field drills with the greatest running and acceleration intensities were straight line conditioning and SSG, respectively. Despite conditioning comprising only 6% of total training time, improvements in aerobic fitness were observed. This suggests dedicating large periods of training to isolated conditioning is unnecessary. Coaches should instead focus on intensity within sports-specific drills, and overall training structure, therefore maximising tactical and technical exposures, whilst still facilitating improvements in fitness. Finally, this study demonstrated that coaches and sports scientists should be cautious in using logistic and linear regression correlations with training load data, as a high degree of multi-collinearity is present within the data.

Chapter 6. Study 3 - The effect of isometric mid-thigh pull grip on the validity and reliability of outcome measures

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Authors' Contributions: Charles Dudley, Jonathon Weakley and Rich Johnston conceptualised the study. All authors contributed to the writing and editing of the manuscript.

Linking statement:

Study one investigated the methods of monitoring training load in adolescent athletes and their relationship to changes in physical qualities, injury, and illness. Using the findings from Study one, Study two was an observational study that investigated the training demands in adolescent rugby players and relationship to changes in physical qualities. However, the methodology used to assess maximal isometric strength in Study two did not follow standard methodological practice. This deviation from standardised methodology was due to time constraints that are common in adolescent environments. As such, Study three sought to examine the validity of practical methods of conducting the IMTP against the criterion method.

6.1 Introduction

Maximal strength is an important physical quality for athletes as it underpins common sporting actions, such as acceleration, jumping, and change of direction [34-36]. Given its importance, practitioners need to be able to assess maximal strength in a practical, valid, and reliable manner. Strength is often assessed through dynamic repetition maximum testing (e.g., one repetition maximum (1RM)) [218], however this can be time consuming and may cause fatigue in athletes as they must complete multiple efforts to find the maximum load that they can move. One alternate method of assessing maximal strength is the IMTP which is a low skill, safe method of assessing full-body maximal isometric strength [37].

The IMTP involves subjects pulling on an immovable bar, in a similar position to the second pull of the clean [37]. To quantify force expression, athletes will either stand on force plates [37], or the bar may be secured to a strain gauge [219]. A common variable of interest in the IMTP is peak force (i.e., the maximum amount of force produced during the pull), which infers full-body maximal isometric strength [37]. Isometric peak force has previously been shown to be a reliable measure and is positively correlated to dynamic actions [34], although it may not be a suitable representation of changes in strength following dynamic resistance training [220]. Additionally, other outcome measures, such as rate of force development (RFD) and impulse, have previously been used to assess time-bound force output [34]. However, while the IMTP is a common method of quantifying global force expression, an important consideration for the completion of this exercise is that the hands are securely fastened onto the bar, as force generation may be limited by the ability to maintain hand contact with the bar.

During the IMTP, methodological guidelines recommend that athletes should be both strapped and taped to the barbell as this mitigates the risk of grip strength being a limiting factor [37]. Despite this, a variety of methodologies, including straps and tape, straps only, bare hands, or allowing the athlete to self-select the method appear in the literature [34, 37, 221]. However, to date, no study has explored how performance outcomes can differ when comparing bare hands to straps and tape. Strapping and taping athletes to the bar increases the time required to perform the test. An alternative method to hold the bar may be the use of figure eight straps, which are commonly used in strength sports and can be applied quickly, do not require constant expenses for strapping tape, yet may provide a similar level of support to straps and tape, whilst being more practical in applied settings. Additionally, the reliability of different methods of gripping the bar has not been explored, and is important information to allow coaches to assess changes in testing results.

Whilst alternative grip methods may increase the feasibility of performing the IMTP, compared to strapping and taping athletes to the bar, they may also influence the validity and reliability of the outcome measures. Therefore, the aim of this study is to: 1) quantify the validity of figure eight wraps and bare hand grip (practical measures) compared to strapped and taped grip (criterion) on force-based outputs; and 2) examine the reliability of these methods.

6.2 Methods

6.2.1 Experimental approach to the problem

A randomised, counter-balanced, repeated measures design was used to assess the criterion-related validity and reliability of the IMTP, performed with different grips. All subjects completed six sessions, with at least 24 hours between trials. The first three sessions were conducted in a randomised order with a) bare hands, b) straps and tape, or c) figure eight straps. This order was then repeated for an additional three sessions. To assess validity, the outcome measures from the initial trials of each condition were used. Additionally, between-day reliability was evaluated by comparing the outcome measure values between testing occasion one and two in each condition.

6.2.2 Subjects

25 subjects were recruited to participate in this study (Male = 18 subjects; Female = 7 subjects; heigh = 176.8 ± 8.9 cm, body mass = 85.2 ± 19.3 kg, age = 27.8 ± 4.2 years). Subjects were all asked to refrain from strenuous exercise for at least 24 hours before testing. A priori power analysis indicated 25 subjects were required to yield statistical power of 80% for peak force ($p = 0.92 – 0.94$; $p0 = 0.80$; $k = 3$; $\alpha = 0.05$) (RStudio 1.2.5033, Vienna, Austria; *ICC.Sample.Size* package, v1.0; Rathbone, Shaw and Kumbhare, 2019). All subjects had >6 months resistance training experience [222], and were free from any musculoskeletal injury, and were experienced with the IMTP. Subjects read and signed written

informed consent forms (2020-1362), with procedures approved by the university human research ethics committee.

6.2.3 Procedures

Upon arrival to the laboratory on the first testing occasion, subject height was measured using a portable stadiometer (Design No.1013522, Surgical and Medical Products, Seven Hills, Australia). While all subjects within this study were familiar and had extensive experience with the IMTP prior to participating, in session one, subjects were re-familiarised with the IMTP procedures and had all procedures carefully explained. Furthermore, subjects were required to demonstrate appropriate technique with bar height adjusted to ensure knee and hip angles of 120–135° and 140–150°, respectively, assessed using a handheld goniometer (Lafayette Extendable Goniometer, Lafayette, Indianapolis, USA) [3]. The position of the bar that allowed these joint angles was recorded and held consistent for each subject for all trials. All IMTP trials were performed using ForceDecks (Vald, Brisbane, Australia), sampling at 1000Hz, standing on a standard IMTP rig (Vald, Brisbane, Australia). Immediately prior to each testing condition, subjects completed an identical, standardised general warm-up, that included bodyweight squats, lunges and core activation exercises, followed by low load dynamic mid-thigh pulls [37].

Following the general warm-up, subjects completed 3 x 3s trials, at 50%, 75% and 90% of maximal effort with 60s rest between trials [37]. Following the warm-up, in the figure eight and straps and tape conditions, subjects were secured to the bar using either figure eight straps, or loop straps and tape, whilst subjects in the bare hands condition grasped the bar with their hands in a double overhand position (Figure 6.1). In the figure eight and straps and tape conditions, subjects hands were secured so minimal movement was possible on the initiation of the pull. In the performance of the IMTP, all protocols were followed as detailed by Comfort et al., [37]. Specifically, subjects were instructed to take the slack out of the bar without excessive pretension and the live force trace was visually inspected to ensure a one second quiet standing period was achieved where change in force was <50N [37]. Subjects were then given the command “On go, push as hard and as fast as possible – 3, 2, 1 GO”. For each attempt, subjects were given identical strong verbal encouragement on all trials – “Pull, Pull, Pull”, with subjects required to complete two successful trials which involved the difference in peak force being <250N. Between 2- and 3-minutes rest was allowed between trials. The trial with the highest peak force was used for analysis. Trials were deemed unsuccessful if the subject failed to achieve a quiet standing period, performed a clear countermovement prior to the initiation of the pull, or had a spike in peak force at the end of the pull, determined through visual inspection of the force trace [37].

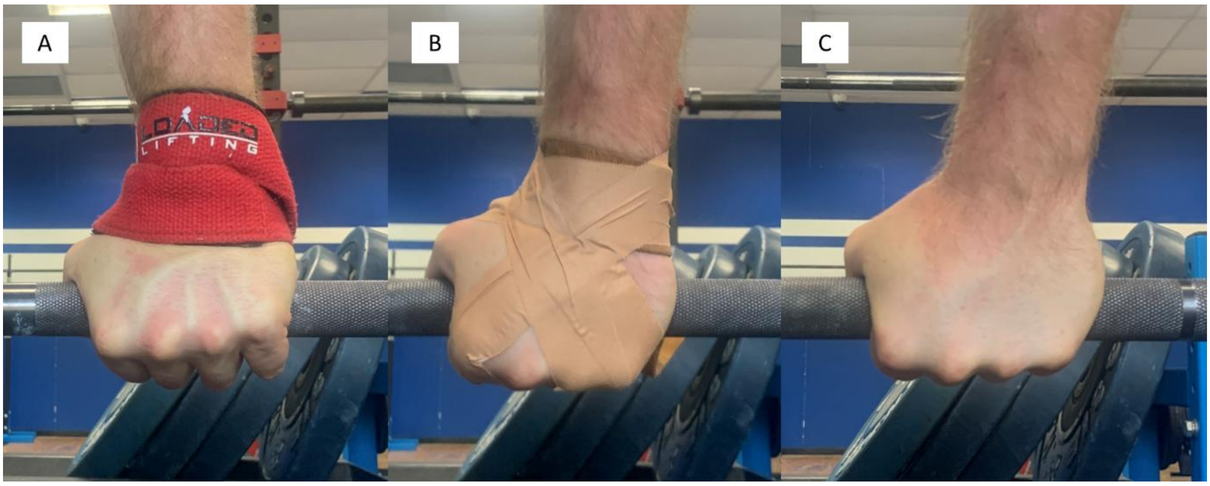

Figure 6.1. Methods of gripping the bar A) Figure eight condition, B) Straps and tape condition, and C) bare hands condition.

Following the testing, all force-time data were extracted from the ForceDecks online portal to a CSV file. Initially, a quiet standing period was identified whereby changes in force were less than 50N [37]. Following the quiet standing period, repetition onset was identified when peak force increased by an amount equal to five times the standard deviation of force recorded during the quiet standing period [37]. Negative onset was identified by both visual inspection of the force-time trace, and a negative movement of five standard deviations of force following the end of the quiet period. Peak force, RFD and net impulse were assessed using a custom-code, with no filtering of the raw time series data using the R statistical programming language (R version 4.2.1, R Foundation for Statistical Computing, Vienna, Austria) within the RStudio environment (Version 1.1.383, Posit, Boston, MA). Peak force was defined as the maximal force output across a single data point within a repetition. RFD was defined as the change in force between onset, and the specific time epoch (e.g., 100ms, 150ms). Impulse was defined as the cumulative force produced between onset and the specific time epochs. Time epochs for

RFD and impulse were selected based on previous research [37]. The end of each repetition was identified by force returning to below the onset threshold.

6.2.4 Statistical Analysis

Data analysis was conducted using the R statistical programming language, with the *dplyr, tidyverse, effsize, caret, rsq, roll, varhandle, ggplot2,* and *pracma* packages. Data were assessed for normality using the Shapiro-Wilks test ($p > 0.05$). Absolute reliability of the variables was determined using the typical error (TE), whereas relative reliability was assessed by the log-transformed coefficient of variation (CV%), expressed as a percentage, and the intraclass correlation coefficient ($\text{model}_{2,k}$). Due to the heterogeneity of the population, smallest worthwhile change was not calculated. Acceptable reliability was deemed as CV% < 10.

To assess validity, comparisons were made between the trials conducted on testing occasion one in each condition using paired-sample *t* tests. To assess the magnitude of the effect between conditions, effect sizes (ES ± 95%CI) were used. Effect sizes of 0.00 – 0.19, 0.20 – 0.49, 0.50 – 0.79 and >0.8 were considered as trivial, small, medium, large, respectively [223]. Unclear effects were identified by the confidence intervals crossing 0.2 on both the positive and negative boundaries. Outcome measures were deemed valid if $p > 0.05$.

For outcome measures that had acceptable reliability, but poor validity, linear regression analysis was used to determine a prediction equation. Additionally, a cross-validation of the prediction equation using a 50/50 random split of the sample was used to determine shrinkage of R^2 relative to the model. Correlations were considered trivial ($r = 0 – 0.09$), small ($r = 0.10 – 0.29$). moderate ($r = 0.30 – 0.49$), large ($r = 0.5 – 0.69$), very large ($r = 0.70 – 0.89$), nearly perfect ($r = 0.90 – 0.99$) and perfect ($r = 1$) [214].

6.3 Results

There were no significant differences for RFD and net impulse across all time bounds. For isometric peak force, differences were unclear between the straps and tape and figure eight condition. However, peak force was significantly lower in the bare hands condition, when compared to both the straps and tape and figure eight conditions (Table 6.1).

Inter-session reliability showed acceptable reliability for peak force in all conditions (CV% = 5.36 - 5.67%) however, RFD and net impulse had lower reliability across all time bounds (Table 6.2).

The overall regression model showed that peak force in the bare hands (practical) condition explained 71.1% of the variance in peak force of the straps and tape (criterion) condition, yielding the equation: Peak force (Straps and tape) = (0.81 × Peak force (bare hands)) + 699.03.

Table 6.1. Results of validity analysis comparing peak force and RFD between conditions.

Condition	ST (mean ± S.D)	F8 (mean ± S.D)	ST Vs. F8 p-value; Effect size ± 95% CI	BH (mean ± S.D)	ST Vs. BH p-value; Effect size ± 95% CI
Peak Force (N)	2856 ± 558	2809 ± 599	0.42; 0.08 ± 1.14	2636.87 ± 541.91	<0.01; 0.4 ± 1.15
RFD50 (N.S)	4614 ± 4351	5128 ± 4483	0.51; -0.13 ± 1.14	5619.2 ± 3439.86	0.21; -0.26 ± 1.14
RFD100 (N.S)	5895 ± 343	5900 ± 3480	0.99; 0.00 ± 1.14	6164.1 ± 2930.06	0.65; -0.08 ± 1.13
RFD150 (N.S)	6231 ± 2748	5920 ± 2829	0.52; 0.12 ± 1.13	5931.53 ± 2564.07	0.57; 0.11 ± 1.14
RFD200 (N.S)	5546 ± 2113	5398 ± 2243	0.66; 0.07 ± 1.14	5109.4 ± 1952.59	0.27; 0.21 ± 1.14
RFD250 (N.S)	4760 ± 1604	4658 ± 1662	0.68; 0.07 ± 1.13	4333.92 ± 1424.21	0.19; 0.28 ± 1.14
RFD300 (N.S)	4321 ± 1387	4103 ± 1423	0.32; 0.16 ± 1.14	3807.37 ± 1308.6	0.08; 0.38 ± 1.14
Impulse at 50ms	4.85 ± 4.87	5.27 ± 4.63	0.61; -0.10 ± 1.14	6.23 ± 3.84	0.13; -0.32 ± 1.15
Impulse at 100ms	25.22 ± 19.15	26.67 ± 19.61	0.66; -0.08 ± 1.14	28.98 ± 15.15	0.26; -0.22 ± 1.14
Impulse at 150ms	63.74 ± 36.93	64.26 ± 38.27	0.93; -0.01 ± 1.13	67.19 ± 31.68	0.59; -0.10 ± 1.14
Impulse at 200ms	115.94 ± 56.51	114.08 ± 58.57	0.84; 0.03 ± 1.13	115.8 ± 49.61	0.99; 0.00 ± 1.14
Impulse at 250ms	173.4 ± 75.26	170.37 ± 78.29	0.80; 0.04 ± 1.14	168.41 ± 66.25	0.72; 0.07 ± 1.14
Impulse at 300ms	235.56 ± 94.87	230.56 ± 96.83	0.73; 0.06 ± 1.13	224.27 ± 83.08	0.52; 0.13 ± 1.14

ST = Straps and Tape, F8 = Figure eight, BH = Bare hands, S.D = Standard Deviation, CI = Confidence Interval

Table 6.2. Inter-day reliability presented as typical error, coefficient of variation and intra-class correlations across all conditions

	Trial 1 ± SD	Trial 2 ± SD	Typical error ± 95% CI	Coefficient of variation ± 95% CI	Intra-class correlations ± 95% CI
Peak Force					
F8	2741 ± 566	2809 ± 599	164.49 ± 100.39	5.67 ± 3.57	0.95 ± 0.1
BH	2628 ± 573	2637 ± 558	133.93 ± 81.73	5.36 ± 3.37	0.95 ± 0.08
ST	2856 ± 542	2819 ± 569	129.47 ± 79.02	4.58 ± 2.87	0.96 ± 0.07
RFD50					
F8	5128 ± 4483	4786 ± 4344	1668.1 ± 1018.09	39.1 ± 28.87	0.89 ± 0.19
BH	5619 ± 4351	5844 ± 3365	2592.47 ± 1582.25	62.29 ± 50.19	0.67 ± 0.46
ST	4614 ± 3440	5335 ± 4055	2878.29 ± 1756.69	105.59 ± 96.98	0.38 ± 0.68
RFD100					
F8	5899 ± 3480	5413 ± 3442	1145.8 ± 699.31	116.86 ± 110.54	0.55 ± 0.57
BH	6450 ± 3239	6164 ± 3435	1887.86 ± 1152.21	86.19 ± 74.96	0.49 ± 0.62
ST	5894 ± 2930	5613 ± 2937	1669.84 ± 1019.14	75.62 ± 63.67	0.4 ± 0.67
RFD150					
F8	5919 ± 2829	5485 ± 3158	1121.46 ± 684.45	37.14 ± 27.2	0.77 ± 0.34
BH	5931 ± 2748	5937 ± 2754	1588.3 ± 969.37	102.45 ± 93.31	0.31 ± 0.71
ST	6230 ± 2564	5713 ± 2618	1567.65 ± 956.77	75.97 ± 64.04	0.31 ± 0.71
RFD200					
F8	5398 ± 2243	4945 ± 2535	866.17 ± 528.64	31.3 ± 22.37	0.75 ± 0.38
BH	5109 ± 2113	5013 ± 2181	1238.63 ± 755.96	79.52 ± 67.77	0.32 ± 0.7
ST	5546 ± 1953	5209 ± 2270	1131.52 ± 690.59	66.76 ± 54.6	0.31 ± 0.71
RFD250 (ms)					
F8	4658 ± 1662	4270 ± 1845	809.94 ± 494.33	27.77 ± 19.54	0.7 ± 0.43
BH	4333 ± 1604	4203 ± 1598	991.9 ± 605.38	77.04 ± 65.15	0.26 ± 0.74
ST	4760 ± 1424	4338 ± 1678	929.53 ± 567.32	56.62 ± 44.71	0.27 ± 0.72
RFD300 (ms)					
F8	4102 ± 1423	3807 ± 1448	726.63 ± 443.48	24.67 ± 17.11	0.7 ± 0.43
BH	3807 ± 1387	3731 ± 1351	869.38 ± 530.6	61.25 ± 49.16	0.28 ± 0.72
ST	4321 ± 1309	3804 ± 1393	822.11 ± 501.75	48.75 ± 37.39	0.3 ± 0.72
Net Impulse at 50ms					
F8	5.13 ± 4.3	5.50 ± 4.58	1.98 ± 1.24	42.34 ± 32.52	0.82 ± 0.3

BH	6.23 ± 4.87	6.18 ± 3.57	3.11 ± 1.9	65.05 ± 52.9	0.65 ± 0.47
ST	4.85 ± 3.84	5.74 ± 4.86	3.63 ± 2.21	121.37 ± 116.09	0.37 ± 0.68
Net Impulse at 100ms					
F8	27.82 ± 19.16	25.61 ± 18.34	6.18 ± 3.87	33.89 ± 25.12	0.86 ± 0.23
BH	28.98 ± 19.15	30.38 ± 16.09	10.71 ± 6.53	69.16 ± 57.03	0.61 ± 0.52
ST	25.22 ± 15.15	26.94 ± 17.23	10.74 ± 6.55	85.67 ± 74.4	0.41 ± 0.66
Net Impulse at 150ms					
F8	64.26 ± 38.27	59.15 ± 38.33	12.04 ± 7.35	49.13 ± 37.75	0.78 ± 0.34
BH	67.19 ± 36.93	69.51 ± 34.31	20.47 ± 12.49	79.98 ± 68.26	0.50 ± 0.61
ST	63.74 ± 31.68	62.62 ± 33.11	19.47 ± 11.88	76.56 ± 64.65	0.39 ± 0.67
Net Impulse at 200ms					
F8	114.08 ± 58.57	105.18 ± 62.81	19.49 ± 11.89	32.75 ± 23.55	0.83 ± 0.28
BH	115.8 ± 56.51	117.41 ± 54.96	30.99 ± 18.91	80.56 ± 68.88	0.44 ± 0.64
ST	115.94 ± 49.61	111.16 ± 53.86	29.87 ± 18.23	73.83 ± 61.81	0.35 ± 0.69
Net Impulse at 250ms					
F8	170.37 ± 78.29	156.7 ± 86.13	27.2 ± 16.6	29.62 ± 21.01	0.81 ± 0.30
BH	168.41 ± 75.26	168.81 ± 75.09	42.2 ± 25.76	78.4 ± 66.59	0.4 ± 0.67
ST	173.4 ± 66.25	164.55 ± 74.49	39.57 ± 24.15	68.28 ± 56.14	0.33 ± 0.70
Net Impulse at 300ms					
F8	230.56 ± 96.83	211.92 ± 107.64	35.88 ± 21.90	27.79 ± 19.55	0.78 ± 0.33
BH	224.27 ± 94.87	222.9 ± 94.12	54.15 ± 33.05	74.35 ± 62.35	0.37 ± 0.68
ST	235.56 ± 83.08	220.03 ± 93.99	49.93 ± 30.48	62.59 ± 50.47	0.31 ± 0.72

ST = Straps and Tape, F8 = Figure eight, BH = Bare hands, RFD = rate of force development at, SD = Standard Deviation, CI = Confidence Interval

6.4 Discussion

This study quantified the validity of figure eight wraps and bare hand grip (practical measures) compared to straps and tape grip (criterion) on force-based outputs. Furthermore, it examined the between-day reliability of these methods. Compared to the straps and tape condition, using only bare hands to grasp the bar reduced peak force values and were unclear for all other outcome measures. Furthermore, all conditions were found to have acceptable reliability (i.e., CV% <10%) for peak force, however, all RFD and impulse outcome measures were not reliable. These results show that practitioners can reliably assess peak force from either bare hand, straps and tape or figure eight straps. However, using bare hands will lead to lower peak force outputs, and therefore may not be appropriate when attempting to accurately assess maximal whole body isometric force production. Additionally, practitioners should not use different methods of gripping the bar interchangeably and it is recommended that either straps and tape or figure eight straps should be used. Figure eight straps may be preferential to straps and tape due to the equivalence in validity and reliability but increased efficiency in setup. Finally, practitioners should only use the IMTP to assess maximal isometric force production, as time-bound metrics demonstrate large amounts of noise that would make tracking change over time difficult.

This study found that figure eight straps, but not bare hands, was a valid method of performing the IMTP. Pulling with bare hands reduced gross peak force by approximately ~200N when compared to the figure eight and straps and tape conditions. The reduction in peak force is likely due to grip strength and/or hand size being the limiting factor which reduces ability to maximally exert force into the platform. Previously, lifting straps have been shown to improve force production in the power clean [224], and clean pull [225] exercises and have been shown to improve perceived grip security [226]. Consequently, given the acceptable validity of the figure eight, but not bare hands conditions, it is recommended that practitioners do not compare results between IMTP attempts when participants are varying their use of straps. Furthermore, due to the reduced time and cost but similar force outputs associated with using figure eight straps compared to the straps and tape condition, practitioners may wish to use figure eight wrist straps when assessing peak isometric force in the IMTP.

Peak force was found to be reliable across all conditions, with CV% ranging from 4.68% to 5.67%. However, this study also found that all RFD and impulse outcome variables have poor reliability (all CV% > 27%). These findings support previous research, that have shown peak force to be reliable, with varied findings for time-bound metrics [227-231]. Time-bound metrics have previously been used to infer early stage force production, and these outcomes have been suggested to be related to changes in athletic performance (e.g., jumping, sprinting and weightlifting) [232]. However, considering that these time-bound outputs demonstrate large amounts of variance, other methods of assessing the ability to express force in a time constrained movement that are both reliable and demonstrate better construct validity, such as jump testing, may be more appropriate [233].

6.5 Conclusion

In conclusion, manipulating the method of grasping the bar will alter the validity and reliability of outcome measures in the IMTP. When compared to the recommended method of using wraps and tape, figure eight straps are a viable alternative whereas bare hands are not. This reduction in force output when only using bare hands is likely due to grip strength being the limiting factor and this undermines the ability of practitioners and researchers to quantify a true maximal effort. Additionally, while peak force was reliable in all conditions, all time-bound metrics of RFD and impulse were found to be unreliable, and these outcomes should not be used during testing. Finally, given the differences in outcome measures, outcomes from the IMTP should only be compared when standardised methodology is used. Therefore, considering the above findings, figure eight straps may be a time efficient method of helping to set up the IMTP whilst ensuring an accurate and reliable measure of peak force is achieved.

6.6 Practical applications

The IMTP is commonly used to assess maximal isometric force capacity. A practitioner who is looking to use the IMTP should use either straps and tape, or figure eight straps to secure athletes to the bar. However, it could be recommended that practitioners use figure eight straps, due to their equivalence in reliability, but increased efficiency and practicality when compared to straps and tape. Conversely, bare hands should not be used due to the reduction in peak force. Additionally, practitioners should be aware that peak force was the only reliable outcome measure, even in individuals who were familiar with the IMTP and were carefully and rigorously standardised across testing occasions. Therefore, practitioners who wish to assess isometric force production in a time constrained period should consider using figure eight wraps but should also be aware that peak force is the only reliable outcome measure.

Chapter 7. Study four - Variability and the effect of manipulation of pitch size and player numbers on the demands of Rugby Union small-sided games

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Authors' Contributions: Charles Dudley, Jonathon Weakley, Rich Johnston and Robert McCafferty conceptualised the design. Charles Dudley and Robert McCaffety collected the data. Charles Dudley analysed the data and all authors contributed to the writing and editing of the manuscript.

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Linking statement:

The findings of study two demonstrated that a significant portion of training time was dedicated to game-based still. As such, to improve prescription of game-based drills, study four investigated the effect of manipulating task constraints on the physical, technical and subjective task-load demands in SSG.

7.1 Introduction

Small-sided games (SSG) are a popular method of training in team sports, such as Rugby Union [234]. SSG are thought to be useful for athletes as they allow physical, tactical, technical and psychological elements of a sport to be trained simultaneously [42, 235]. However, altering the constraints of small-sided games has been shown to influence factors that are important to developing physical capacities and technical skills, such as training intensity (e.g., m/min) and technical exposures (e.g., passes per player) [82, 85]. Consequently, designing SSG that can target certain physical, tactical, technical, or psychological elements is important for coaches to ensure games are specific to the desired outcomes. One method that alters the outcomes of SSG is task constraint manipulation [42, 236].

The constraints of SSG (e.g., pitch size and player numbers) can be manipulated to elicit different outcomes[237]. For example, changing the field size from 400m^2 to 2800m^2 with junior rugby league players increased the distance covered by ~15 meters per minute [81]. However, the study employed "offside touch" games [81], whereby players can be in an "offside" position and pass the ball in any direction, altering the physiological and skill demands of the game [88]. Additionally, altering the number of players on the pitch can change the number of technical exposures [82, 85]. There is currently limited research into the effect of manipulating task constraints on physical demands in onside Rugby Union SSG. Therefore, developing an understanding of how constraint manipulating influences game demands allows coaches to plan training loads and target certain qualities accordingly.

The training practices of adolescent athletes, and the subsequent physiological responses can be measured through external and internal load monitoring tools [29, 210]. Global navigation satellite systems (GNSS) and accelerometry have been used extensively in adolescent Rugby Union [215]. However, some previous research investigating the effect of pitch size on external demands was performed using GNSS units that have been shown to have poor reliability at high speeds [238]. Additionally, internal load measures, such as HR or sRPE can be used to assess responses to the external load [30]. Despite the high frequency of acceleration and decelerations in Rugby Union, average acceleration demands have not previously been reported for SSG [42, 239]. Acceleration and deceleration demands have been associated with common fatigue markers including soreness, creatine kinase concentration, and decreases in neuromuscular function [240, 241]. Understanding both the internal and external demands of SSG may assist coaches in planning effective training practices.

One of the benefits of SSG is that they can be used to practice technical skills, in addition to developing physical capacity [81, 85, 242], whilst also exposing athletes to a variety of psychological situations. Skill development through a games-based approach is thought to be more effective than traditional, closed drills, due to greater specificity [243]. However, there is conflicting research as to the variability of skill exposure when task constraints are identical [244, 245]. Further, it is not currently known how manipulating pitch size and player numbers may influence technical exposures in Rugby Union SSG. Understanding the technical demands of SSG, and the effect of constraint manipulation, may alter the exposure to skilful tasks (e.g., catching, passing), in a variable environment. Altering constraints will also change subjective task-loads which are important in understanding the psychological demands of different drills [94].

To fully understand the influence of constraint manipulations on SSG it is important to examine the changes in technical, tactical, physical, and task-load demands. Accordingly, the aims of this study were to assess the effect of manipulation of pitch size and player numbers in SSG on the physical, technical, and subjective task-load demands in adolescent Rugby Union players during an on-side touch game. Additionally, this study assessed the variability of physical, technical, and subjective task-load demands in SSG. It was hypothesized that reducing pitch size and increasing player numbers would increase the movement demands; that reducing player numbers would increase the technical exposures, with no effect for pitch size; and that reducing pitch size and increasing player numbers would increase subjective task load scales such as level of effort and physical demands. Additionally, it was hypothesized that physical demands would have low variability, whilst technical exposures and subjective task-loads would have high variability.

7.2 Methods

This study assessed the effects of pitch size and player number manipulation on the physical, physiological, technical, and subjective task-load demands in adolescent Rugby Union players using a crossover study design. A convenience sample of twenty-six adolescent males volunteered to participate within this study (mean ± SD, age: 16.0 ± 1.0 years, height: 1.76 ± 0.06 m, body mass: 75.85 ± 11.67 kg, years from peak height velocity: 1.28 ± 0.86, MAS: 3.75 ± 0.28 $m{\cdot}s^{-1}$, MSS: 8.45 ± 0.43 $m{\cdot}s^{-1}$). All subjects had at least two years' experience in Rugby Union and were in a schoolboy "performance squad", indicating they had significant previous experience in Rugby Union. Teams during the SSG were pair matched according to athlete MAS, with each teams opposition decided randomly. If subjects were unable to attend the training session ($n = 3$) they were replaced with a player with similar MAS. Ethics approval was granted by the Australian Catholic University human research ethics committee (2022-2717H). All subjects and parents were provided with an information letter and gave written assent, along with parental consent.

All subjects completed seven sessions within a three-week period. In the first session, subjects were familiarised with the SSGs, and completed anthropometric screening (standing height, seated height, and body mass) and physical testing (40m sprint, 2km time trial). In sessions two and three, subjects completed a 6 vs. 6 game on a medium-sized pitch as the reference condition to establish reliability. In sessions four and five, the pitch size was manipulated using a counterbalanced design and player numbers were manipulated in sessions six and seven (Table 7.1). Pitch size was determined using common landmarks on the pitch, and ensuring similar player densities to those previously reported [82, 91, 246]

Table 7.1. Conditions included within the experimental protocol

Constraints	Control	Pitch size		Player Number	
Pitch size	Medium (Width:30m, Length: 40m)	Small (Width: 25m, Length: 30m)	Large (Width: 35m, Length: 50m)	Medium (Width:30m, Length: 40m)	Medium (Width:30m, Length: 40m)
Player Numbers	6 v 6	6 v 6	6 v 6	12 v 12	4v4
Player Density	100m^2 per player	73m^2 per player	130m^2 per player	50m^2 per player	150m^2 per player

Subject standing and seated height were recorded using a stadiometer (Design No.1013522, Surgical and Medical Products, Seven Hills, Australia). Maturation was estimated using the Mirwald equation [96].

Maximal sprint speed was assessed using a 40m linear sprint. Two markers were placed 40m distance away from each other, on a dry, synthetic outdoor running track. Subjects begun in a two point stance, immediately behind a marker, and self-initiated the start of the sprint [102]. Each subject was allowed two attempts, separated by approximately three minutes. Maximal sprint speed was recorded using a 10 Hz GNSS device (Catapult Optimeye X4 and S5; Catapult Innovations, Melbourne, Australia), which is valid in assessing MSS (mean bias= -0.77% (90%CI -1.13 to -0.42) [29, 247]. To assess aerobic fitness, subjects completed a 2km time trial on the same 400 m running track. The 2km time trial was selected as it has previously been shown to have strong relationships to maximal aerobic speed [98] and has demonstrated acceptable reliability (CV 1.9%; ICC 0.95) [99]. Time was assessed via a hand-held stopwatch (Regent 240 Econo Sports Stopwatch, Regent, Victoria, Australia) and manually recorded. All subjects were encouraged to give a maximum effort throughout the 2km trials. The result of the 2km time trial was then used to infer MAS using the Bellenger equation [98]. Anaerobic speed reserve (ASR) was then calculated by subtracting MAS from MSS [248].

7.2.1 Small-sided game rules

All games used the same modified, onside, “touch” rules. These rules required the tackler to touch the ball carrier with two hands to simulate a tackle. After a touch, the tackler completed a modified burpee, which involved the tackler going to ground and rolling to simulate the post tackle sequence, while the ball carrier went to ground, and passed to a support player. Each team had six touches before a turnover occurs on the sixth, or a knock-on (i.e., the ball was dropped and went forward) occurred. When a try was scored, the team that scored the try remained in possession of the ball and played in the opposite direction to facilitate continuity of play. If the ball went out of bounds, referees would immediately feed a new ball to the opposition of the team that last touched the ball. The same referees were used throughout all sessions, with consistent encouragement to the players.

7.2.2 Match Demands

All sessions were completed with subjects' wearing a 10 Hz GNSS (Catapult Optimeye X4 and S5; Catapult Innovations, Melbourne, Australia) device secured between subjects shoulder blades using a fitted bib. These devices have been shown to be reliable over multiple days for measuring the variables of interest [185]. All subjects were assigned a GNSS unit to be used throughout the data entire collection period. Signal quality throughout the period of data collection was adequate, as the average number of satellites was 12.6 ± 3.0, and the average horizontal dilution of precision was 0.77 ± 0.11 [249]. GNSS units were turned on 15 minutes prior to the start of each session. Data were downloaded using OpenField (Catapult Innovations, Melbourne, Australia). In addition to average running speed, running was categorised into five individualised velocity bands, <60% MAS, 60-79% MAS, 80 – 99% MAS, 100% MAS – 29% ASR, and >30% ASR [250]. Relative velocity zones were used as it has been demonstrated that the use of arbitrary speed thresholds is likely to inaccurately estimate the workloads performed [251]. Additionally, acceleration load, and acceleration density index were collected [252]. Acceleration density index is the ratio between acceleration load and total distance (i.e., acceleration load per 10 m) [253].

All subjects wore a HR monitor (H10, Polar, Oy, Finland), that was secured to the subject's chest with an elastic strap. HR monitors were synced to the subjects GNSS unit, and data downloaded using Openfield. Variables assessed were average and maximal HR. Additionally, to assess the perceived internal response to training load, 15 minutes following the end of the touch games subjects completed a written sRPE questionnaire using the Borg category-ratio 10 scale, which has previously been validated in adolescent athletes [28, 106, 254]. Subjects completed the sRPE questionnaires independently and blinded from other subjects to control for peer influence [255].

The National Aeronautics and Space Administration Task-load Index (NASA-TLX) was used to assess subjective task-related workload [256]. The NASA-TLX has been previously validated and is comprised of six scales, representing physical, mental and temporal demands, as well as levels of frustration, effort and performance [256, 257]. Subjective task-load is the perceived effort or cost incurred to achieve a level of performance, based on all elements of a task, and has previously been related to increased fatigue and reduced athletic performance [258, 259]. Each scale is made up of 21 gradations, between "Very Low" and "Very High". Subjects completed the NASA-TLX, approximately 15 minutes following each condition, by writing an X on the scale. Subjects completed the NASA-TLX independently and blinded from other subjects to control for peer influence [255].

To assess the technical and tactical demands, games were filmed using a VEO Camera 1.0 (VEO Technologies, Copenhagen Denmark), raised on a 7.3 metre tripod. To determine intra-rater reliability, a single game was selected at random, and re-analysed two weeks following initial analysis (ICC = 1.00). To ensure appropriate interrater reliability, a single game was selected at random and all technical variables were analysed by a second observer (ICC = 1.00). Technical variables that were selected are commonly performed actions in Rugby Union and have been previously reported in SSG research (Table 7.2) [42, 260].

Table 7.2. Technical variable descriptors

Technical variable	Definition
Successful pass	The ball is transferred between two attacking players
Unsuccessful pass	An attacking player unsuccessfully attempts to transfer the ball to a teammate
Successful catch	An attacking player successfully catches the ball
Unsuccessful catch	An attacking player, who is in a realistic position to catch a pass from their teammate, fails to do so

Touches	A defensive player(s) makes a two-handed tag on the ball carrier
Passes per touch	The number of passes between touch events

7.2.3 Statistical analysis

Unless indicated, data are presented as mean ± standard deviation (SD). To determine whether continuous dependent variables (e.g., m/min, average acceleration) were significantly different between conditions, linear mixed effects models with gaussian regression were used, whereby condition (i.e., pitch size or player number) was a fixed effect, and subject ID was included as a random intercept. Post-hoc pairwise comparisons were performed with a Tukey adjustment to account for multiple comparisons. Separate models were built for each outcome variable of interest (e.g., m/min, percent maximum velocity (%VMAX), and acceleration density). To assess count variables (i.e., number of passes, catches, and TLX subscales), generalised linear mixed-effects models with Poisson regression were used; with separate models were built for each outcome variable of interest. To assess the magnitude of the differences Cohens *d* effect sizes were estimated from the *t* statistics [214, 261]. Effect sizes were considered trivial ($d = 0.00 – 0.19$), small ($d = 0.20 – 0.49$), medium ($d = 0.50 – 0.79$) and large ($d = \geq 0.8$) [223]. Confidence intervals were constructed using pooled standard deviations. Unclear effects were identified by the confidence intervals crossing 0.2 on both the positive and negative boundaries. Statistical significance was set at $p < 0.05$ for all analyses.

Reliability was assessed in the 6 vs. 6 condition, on a medium sized pitch. Absolute reliability of all variables was assessed by the typical error of the measurement. Relative reliability for continuous was determined via a log-transformed within subject coefficient of variation (CV), expressed as a percentage. Relative reliability for count variables was assessed using the CV median absolute deviation method [185]. Additionally, the intraclass correlation coefficient (ICC) ($\text{model}_{2,k}$) was reported. Reliability data were calculated using a purpose made excel spreadsheet [262]. Acceptable reliability was deemed as CV% < 10. All other statistical analyses were performed using the R statistical programming language (R version 4.2.1, R Foundation for Statistical Computing, Vienna, Austria) within the RStudio environment (Version 1.1.383, Posit, Boston, MA).

7.3 Results

The mean ± SD results for physical, technical, and subjective task-load demands can be found in Table 7.3. Additionally, the reliability for all reported variables can be found in Table 7.4.

Table 7.3. Description of the physical, technical, and subjective task-load demands in each condition.

Field size	Medium	Medium	Medium	Large	Small
Player number	6 vs. 6	12 vs. 12	4 vs. 4	6 vs. 6	6 vs. 6
External physical demands					
% Maximum velocity (m/s)	84.7 ± 0.1	76.9 ± 0.1	86.7 ± 0.1	86.4 ± 0.1	78.5 ± 0.1
Distance < 60% MAS	630.7 ± 63.9	661.7 ± 56.0	599.0 ± 55.7	616.1 ± 68.7	653.8 ± 62.9
Distance 60 - 80% MAS	279.4 ± 72.4	206.3 ± 41.9	298.2 ± 64.1	277.7 ± 62.6	258.9 ± 54.8
Distance 80 - 100% MAS	204.0 ± 50.9	137.8 ± 35.7	245.8 ± 59.3	221.4 ± 47.6	171.19 ± 32.7
Distance 100% MAS - 30% ASR	170.0 ± 63.2	105.8 ± 48.3	204.4 ± 51.6	188.7 ± 50.1	133.63 ± 43.0
Distance >30% ASR	75.6 ± 37.4	29.5 ± 21.7	90.3 ± 29.8	74.6 ± 37.6	39.65 ± 22.8
Acceleration Density	0.6 ± 0.1	0.5 ± 0.1	0.6 ± <0.1	0.6 ± <0.1	0.61 ± 0.1
Acceleration Density Index	3.2 ± 0.3	3.3 ± 0.2	3.2 ± 0.2	3.1 ± 0.3	3.52 ± 0.3
Metres per minute	113.3 ± 9.0	95.1 ± 7.4	119.8 ± 8.6	114.9 ± 7.6	104.8 ± 6.6
Internal physical demands					
Mean heart rate	168.8 ± 13.6	166.8 ± 7.2	171.6 ± 7.6	168.8 ± 13.6	164.8 ± 12.1
Maximum heart rate	193.4 ± 10.6	188.3 ± 6.6	190.0 ± 6.9	193.4 ± 10.6	188.6 ± 11.4

sRPE	5.3 ± 1.2	4.1 ± 1.5	7.1 ± 0.9	5.6 ± 1.2	5.0 ± 1.3
Subjective task-load					
TLX Mental	53.0 ± 18.9	52.8 ± 22.3	66.3 ± 22.3	56.5 ± 20.7	55.2 ± 17.5
TLX Physical	64.6 ± 16.4	47.0 ± 19.9	80.5 ± 12.7	69.0 ± 15.1	62.7 ± 16.7
TLX Temporal	68.3 ± 20.0	53.5 ± 19.6	71.5 ± 18.9	66.0 ± 17.9	58.3 ± 18.64
TLX Performance	44.4 ± 23.7	42.4 ± 26.2	37.5 ± 24.4	32.5 ± 22.9	37.5 ± 22.1
TLX Effort	67.5 ± 18.6	58.7 ± 17.7	78.5 ± 15.0	74.0 ± 15.9	67.3 ± 13.4
TLX Frustration	40.0 ± 23.9	41.5 ± 31.6	35.2 ± 24.8	39.0 ± 21.9	39.4 ± 19.5
Technical demands					
Total Involvements	25.89 ± 5.9	16.63 ± 5.1	26.8 ± 7.1	25.2 ± 5.8	28.0 ± 5.4
Successful pass	8.30 ± 3.6	3.04 ± 2.7	10.1 ± 5.2	8.8 ± 4.7	7.9 ± 4.1
Unsuccessful pass	0.79 ± 0.88	0.46 ± 0.66	1.09 ± 0.85	0.54 ± 0.59	0.88 ± 1.08
Successful catch	15.83 ± 4.8	9.54 ± 4.4	18.6 ± 6.8	15.1 ± 4.2	16.9 ± 4.5
Unsuccessful catch	0.32 ± 0.7	0.29 ± 0.5	0.5 ± 0.7	0.4 ± 0.6	0.7 ± 1.0
Carry	8.26 ± 3.5	6.54 ± 3.2	8.4 ± 4.1	8.0 ± 2.5	9.5 ± 2.6

Passes per touch	1.50 ± 1.4	0.93 ± 1.5	1.7 ± 1.0	1.4 ± 1.3	1.0 ± 0.60

Data are mean ± standard deviation. MAS = Maximal aerobic speed, ASR = Anaerobic speed reserve, MSS = maximal sprint speed, sRPE = session ratings of perceived exertion, TLX = Task-load index, Small = Width: 25m, Length: 30m, Medium = Width:30m, Length: 40m, Large = Width:35m, Length:50m.

Table 7.4. Reliability statistics for physical, tactical, and subjective task-load demands

Variables	TE (90% CI)	CV (90% CI)	ICC (90% CI)	SWC
External Physical Demands				
% Maximum velocity	0.07 (0.06 - 0.1)	9.56 (7.59 - 13.08)	0.46 (0.13 - 0.70)	0.02
Distance < 60% MAS	31.78 (25.48 - 42.77)	5.24 (4.18 - 7.11)	0.77 (0.58 - 0.88)	12.91
Distance 60 - 80% MAS	44.28 (35.5 - 59.6)	16.09 (12.71 - 22.25)	0.56 (0.26 - 0.76)	13.64
Distance 80 - 100% MAS	36.62 (29.36 - 49.29)	19.72 (15.52 - 27.41)	0.45 (0.11 - 0.69)	9.65
Distance 100% MAS - 30% ASR	34.37 (27.56 - 46.26)	28.08 (21.95 - 39.53)	0.61 (0.33 - 0.79)	12.25
Distance >30% ASR	27.39 (21.85 - 37.18)	51.18 (39.07 - 75.26)	0.34 (-0.02 - 0.62)	7.04
Acceleration Density	0.03 (0.02 - 0.03)	4.38 (3.49 - 5.93)	0.71 (0.47 - 0.85)	0.01
Acceleration Density Index	0.19 (0.15 - 0.26)	6.09 (4.85 - 8.28)	0.53 (0.22 - 0.74)	0.05
Metres per minute	5.27 (4.22 - 7.09)	4.67 (3.72 - 6.33)	0.61 (0.32 - 0.79)	1.59
Internal Physical Demands				
Average Heart Rate	6.57 (5.27 - 8.85)	4.12 (3.29 - 5.58)	0.78 (0.6 - 0.89)	2.68
Max Heart Rate	8.35 (6.7 - 11.25)	4.28 (3.42 - 5.8)	0.41 (0.07 - 0.67)	2.08
sRPE	0.71 (0.57 - 0.95)	15.08 (11.92 - 20.81)	0.69 (0.45 - 0.84)	0.22

Subjective Task-load				
TLX Mental	5.73 (4.59 - 7.71)	9.09 (7.29 - 12.24)*	0.94 (0.88 - 0.97)	3.80
TLX Physical	7.28 (5.84 - 9.8)	7.14 (5.73 - 9.61)*	0.81 (0.64 - 0.9)	3.21
TLX Temporal	6.09 (4.88 - 8.2)	6.67 (5.34 - 8.97)*	0.95 (0.9 - 0.98)	4.03
TLX Performance	7.28 (5.84 - 9.8)	12.50 (10.02 - 16.82)*	0.93 (0.86 - 0.96)	4.81
TLX Effort	4.17 (3.35 - 5.62)	7.14 (5.73 - 9.61)*	0.94 (0.88 - 0.97)	3.59
TLX Frustration	6.52 (5.23 - 8.78)	17.65 (14.15 - 23.75)*	0.88 (0.77 - 0.94)	4.88
Technical Demands				
Total Involvements	4.24 (3.4 - 5.7)	25.00 (20.04 - 33.65)*	0.37 (0.03 - 0.64)	1.06
Successful pass	2.38 (1.9 - 3.2)	0.29 (0.38 - 0.23)*	0.7 (0.46 - 0.84)	0.75
Unsuccessful pass	0.81 (0.65 - 1.1)	1.00 (1.35 - 0.80)*	N/A	0.18
Successful catch	3.89 (3.12 - 5.23)	25.00 (20.04 - 33.65)*	0.24 (-0.12 - 0.55)	0.91
Unsuccessful catch	0.51 (0.41 - 0.69)	N/A	0.38 (0.03 – 0.64)	0.13
Touches	2.44 (1.95 - 3.28)	25.00 (20.04 - 33.65)*	0.52 (0.21 - 0.74)	0.64
Passes per touch	0.72 (0.58 - 0.97)	52.38 (40.17 - 76.29)	0.64 (0.37 - 0.81)	0.29

* = Coefficient of variation calculated using median absolute deviation, TLX = Task-load index, MAS = Maximal aerobic speed, ASR = Anaerobic speed reserve, sRPE = session ratings of perceived exertion, CV = coefficient of variation, TE = Typical Error, ICC = Intra-class correlation, SWC = Smallest worthwhile change.

7.3.1 Physical demands

Pitch size

For physical demands, there were no significant between the Medium and Large pitch size conditions (Figure 7.1).

When comparing the Small and Large pitch conditions, there was a general trend for greater high-velocity movements in the Large condition, with five physical variables significantly greater in the large condition, and two greater in the small condition (refer to Figure 7.2). These results were similar when comparing the Medium and Small conditions (refer to Figure 7.3). There was no trend for HR response with changes in pitch size.

For technical demands, there were no differences between the Medium and Large conditions, or the Small and Large conditions. When comparing the Small and Medium condition, there were two variables that were greater in the small condition (refer to Table 7.5).

For subjective task-load, there was one significant difference in the Medium and Large condition, favouring the medium condition. There was no difference in the Large and Small conditions, and one in the Medium and Small condition, favouring medium (refer to Table 7.6).

Player number

For physical demands, there were significant differences between the 4 vs. 4 and 6 vs. 6 conditions, with five variables greater in the 4 vs. 4 conditions, and two variables significantly greater in the 6 vs. 6 condition (refer to Figure 7.4).

In the 6 vs. 6 and 12 vs. 12 conditions, nine variables were significantly greater in the 6 vs. 6 condition, and one was significantly greater in the 12 vs. 12 (refer to Figure 7.5). HR responses were also greater in the 6 vs. 6 condition.

In the 4 vs. 4 and 12 vs. 12 conditions, eight variables were significantly greater in the 4 vs. 4 condition, while two were significantly greater in the 6 vs. 6 condition (refer to Figure 7.6).

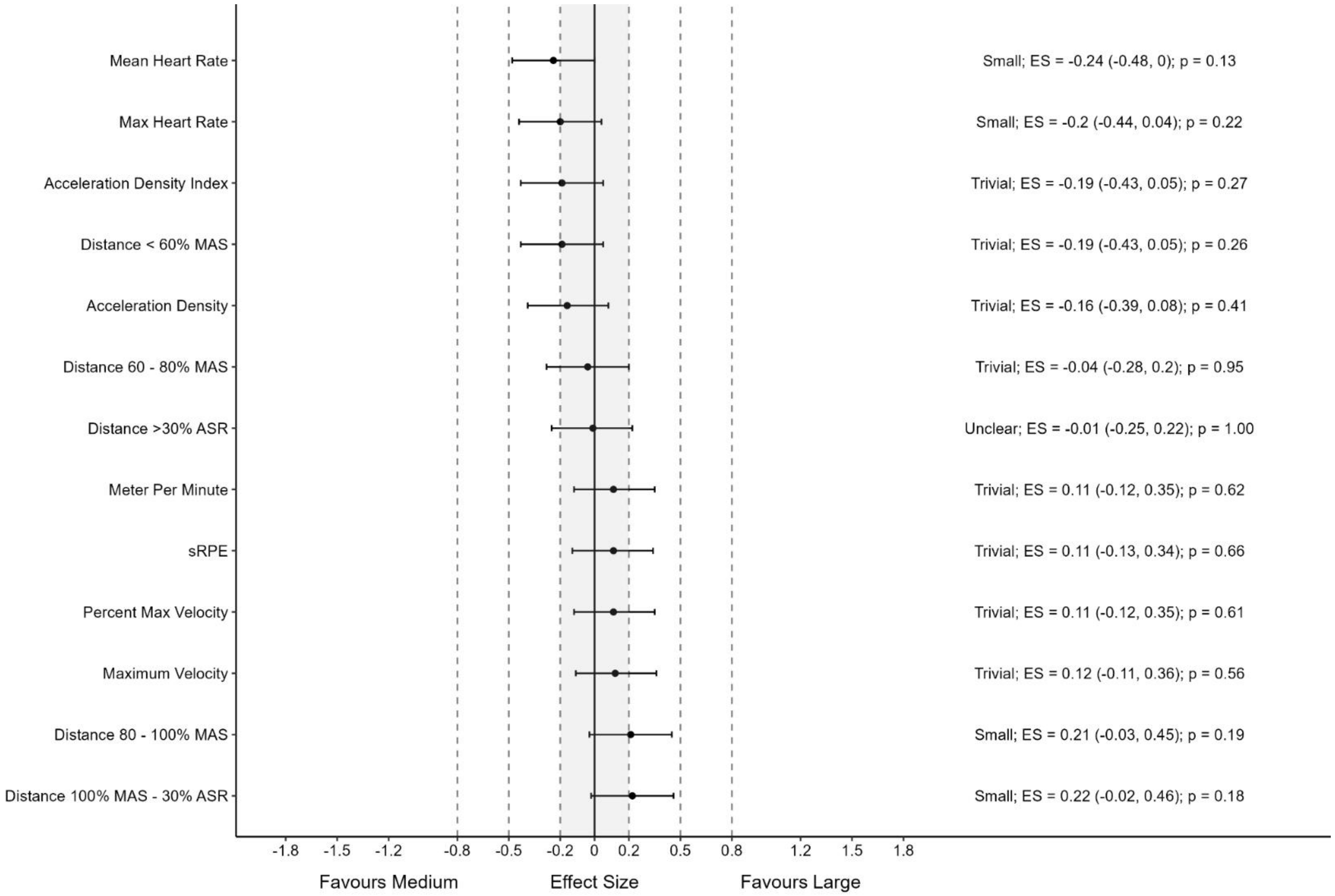

Figure 7.1. Difference in physical demands between medium 6 vs. 6 and large 6 vs. 6 conditions. Data are Cohens d effect size ± 95%CI. * = $p < 0.05$, ** = $p < 0.01$, *** = p 0.001. Dashed horizontal lines represent ES threshold for small, medium and large effects. MAS = Maximal aerobic speed, ASR = Anaerobic speed reserve, sRPE = session rating of perceived exertion.

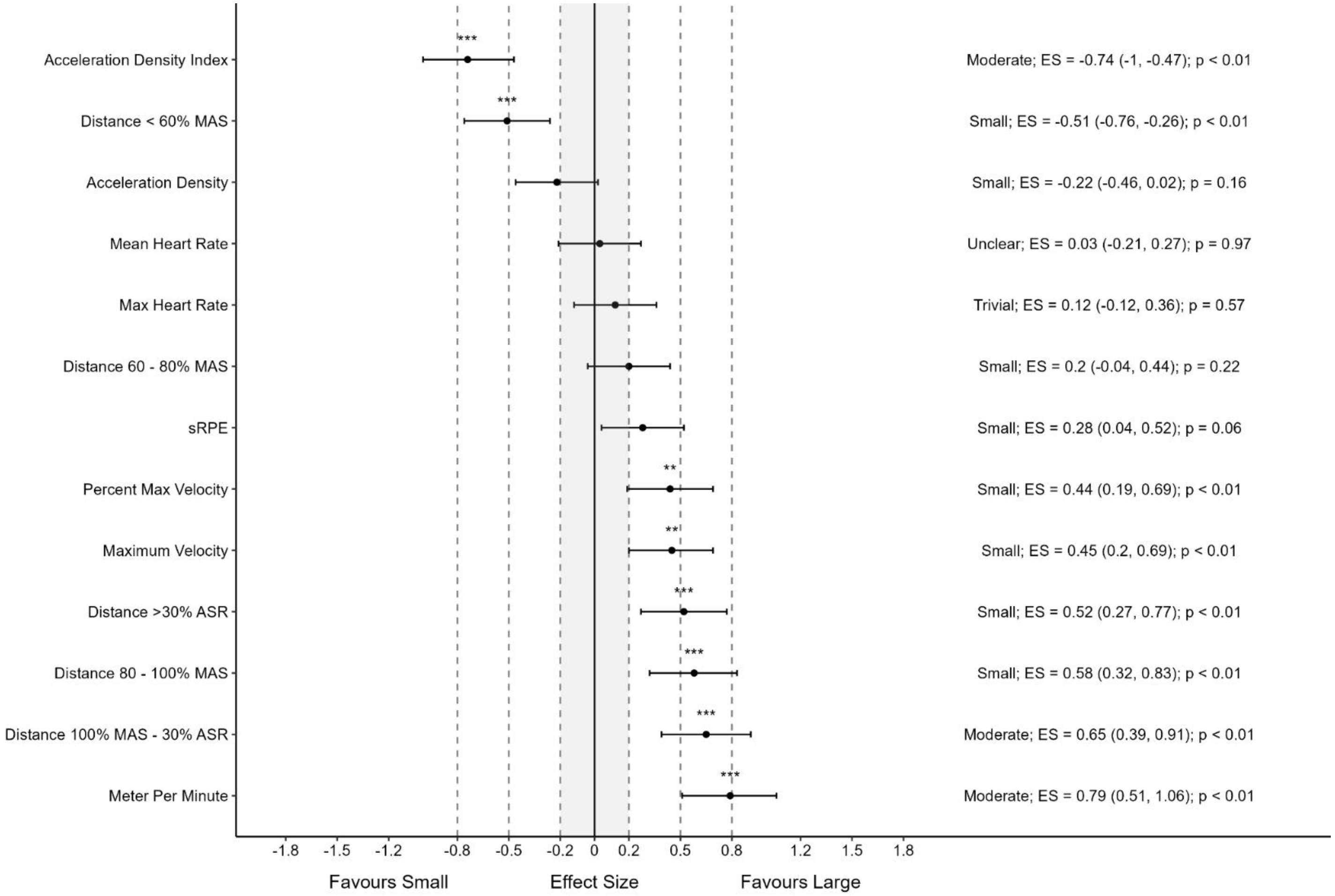

Figure 7.2. Difference in physical demands between small 6 vs. 6 and large 6 vs. 6 conditions. Data are Cohens d effect size ± 95%CI. * = p < 0.05, ** = p < 0.01, *** = p 0.001. Dashed horizontal lines represent ES threshold for small, medium and large effects. MAS = Maximal aerobic speed, ASR = Anaerobic speed reserve, sRPE = session rating of perceived exertion.

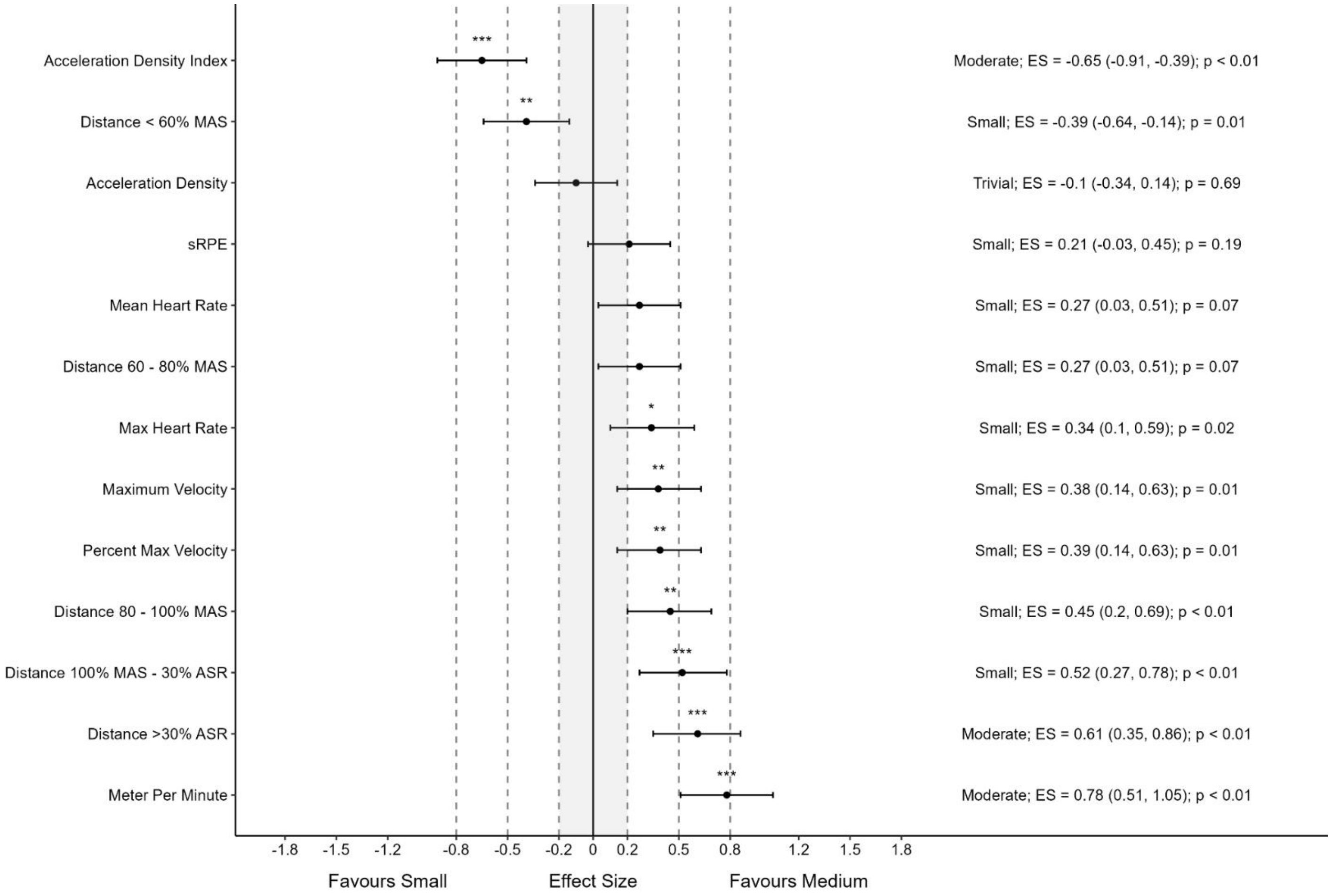

Figure 7.3. Difference in physical demands between small 6 vs. 6 and medium 6 vs. 6 conditions. Data are Cohens d effect size ± 95%CI. * = $p < 0.05$, ** = $p < 0.01$, *** = p 0.001. Dashed horizontal lines represent ES threshold for small, medium and large effects. MAS = Maximal aerobic speed, ASR = Anaerobic speed reserve, sRPE = session rating of perceived exertion.

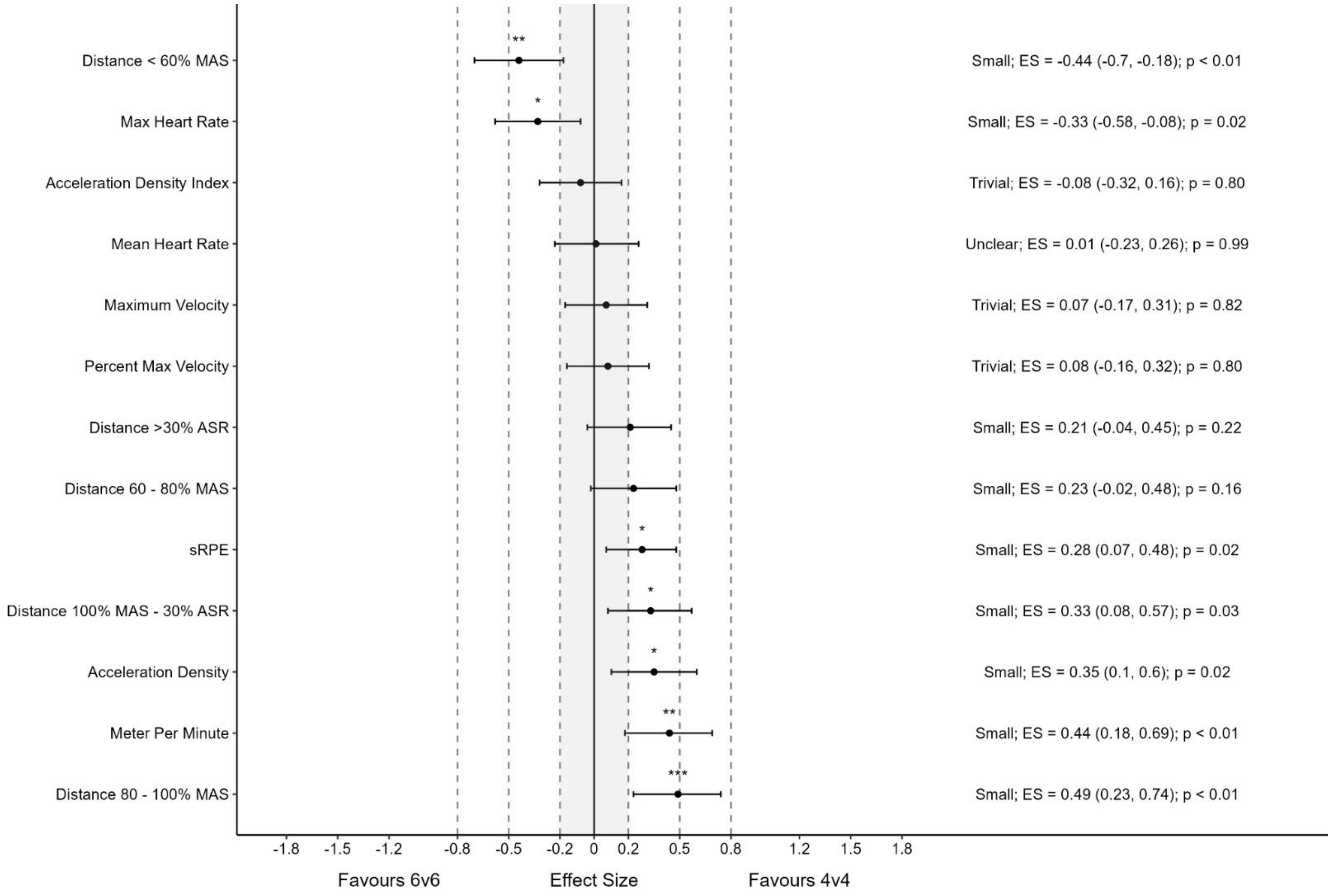

Figure 7.4. Difference in physical demands between medium 6 vs. 6 and medium 4 vs. 4 conditions. Data are Cohens d effect size ± 95%CI. * = $p < 0.05$, ** = $p < 0.01$, *** = p 0.001. Dashed horizontal lines represent ES threshold for small, medium and large effects. MAS = Maximal aerobic speed, ASR = Anaerobic speed reserve, sRPE = session rating of perceived exertion.

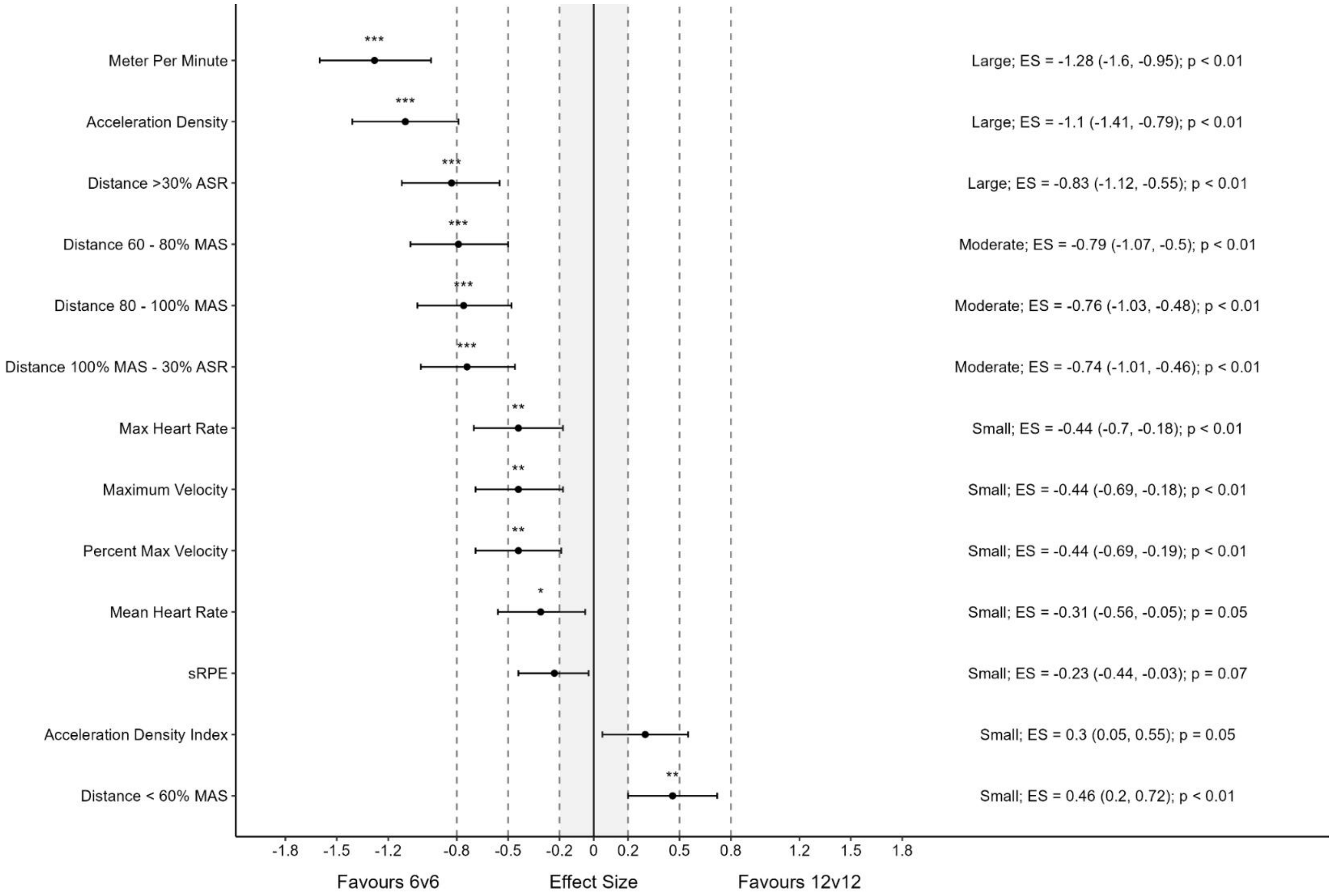

Figure 7.5. Difference in physical demands between medium 6 vs. 6 and medium 12 vs. 12 conditions. Data are Cohens d effect size ± 95%CI. * = $p < 0.05$, ** = $p < 0.01$, *** = p 0.001. Dashed horizontal lines represent ES threshold for small, medium and large effects. MAS = Maximal aerobic speed, ASR = Anaerobic speed reserve, sRPE = session rating of perceived exertion.

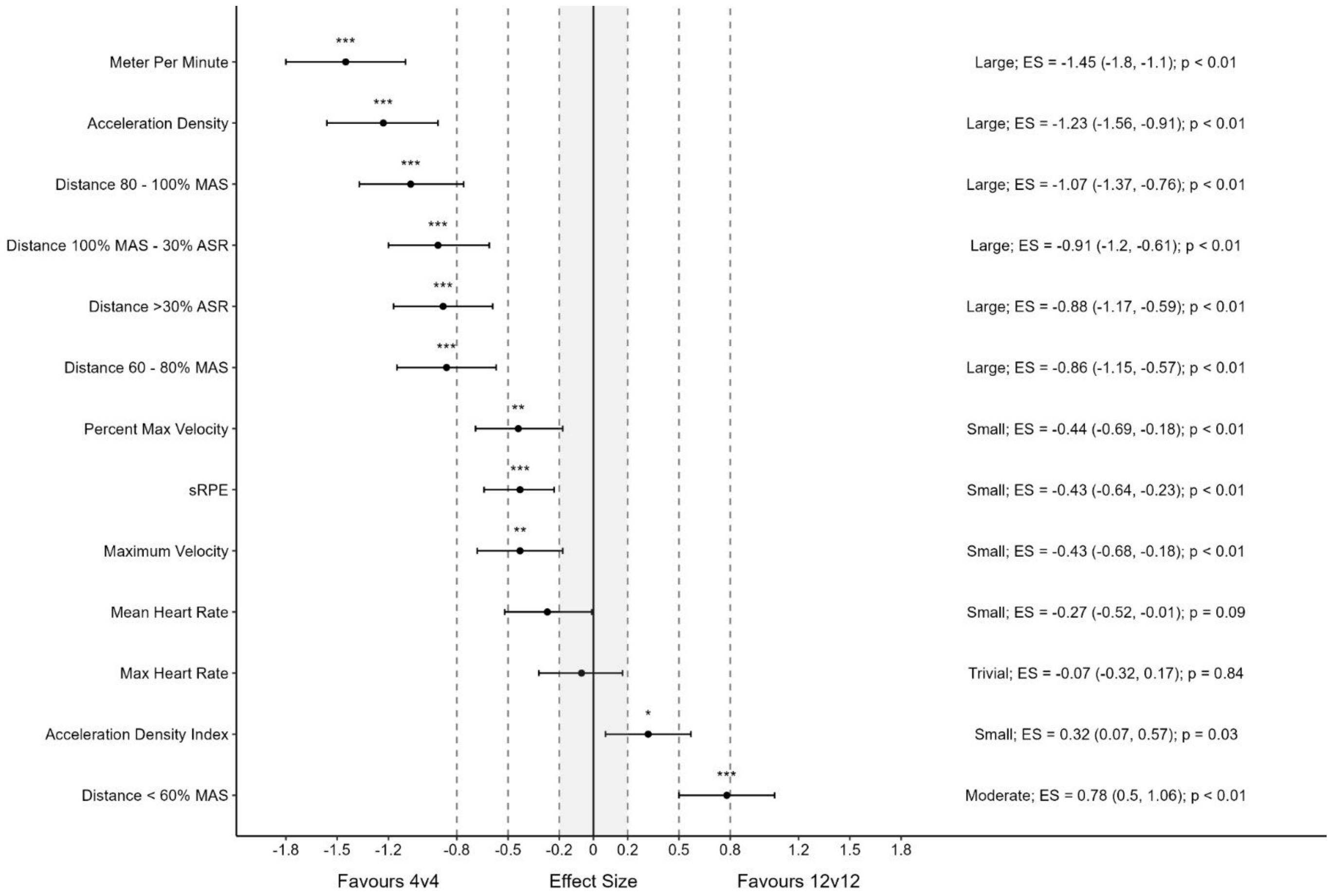

Figure 7.6. Difference in physical demands between medium 4 vs. 4 and medium 12 vs. 12 conditions. Data are Cohens d effect size ± 95%CI. * = $p < 0.05$, ** = $p < 0.01$, *** = p 0.001. Dashed horizontal lines represent ES threshold for small, medium and large effects. MAS = Maximal aerobic speed, ASR = Anaerobic speed reserve, sRPE = session rating of perceived exertion.

7.3.2 Technical demands

For technical variables, in the 4 vs. 4 and 6 vs. 6 conditions, two were significantly greater in the 4 vs. 4., In the 4 vs. 4 and 12 vs. 12 conditions, two variables were significantly greater in the 4 vs. 4 condition. In the 6 vs. 6 and 12 vs. 12 conditions, four variables were significantly greater in the 6 vs. 6 (refer to Table 7.5).

7.3.3 Subjective task-loads

For subjective task-load, in the 4 vs. 4 and 6 vs. 6 condition, two variables were significantly greater in the 6 vs. 6 and three were significantly greater in the 4 vs. 4 condition. In the 4 vs. 4 and 12 vs. 12 conditions, four subjective task-load variables were significantly greater in the 4 vs. 4 condition, and two were significantly greater in the 12 vs. 12 condition. In the 6 vs. 6 and 12 vs. 12 condition, three variables were significantly greater in the 6 vs. 6 condition (refer to Table 7.6).

Table 7.5. Effect of differences in player numbers on subjective task-load and tactical and technical demands.

Field size	Medium	Medium	Medium
Player number	6 vs. 6 × 12 vs. 12	6 vs. 6 × 4 vs. 4	4 vs. 4 × 12 vs. 12
Subjective Task-load			
Effort	p < 0.01; ES = -0.53 (-0.73, -0.32); Small	p < 0.01; ES = 0.4 (0.20, 0.61); Small	p < 0.01; ES = -0.8 (-1.01, -0.59); Large
Frustration	p = 0.28; ES = 0.16 (-0.05, 0.37); Trivial	p = 0.01; ES = -0.31 (-0.52, -0.11); Small	p < 0.01; ES = 0.41 (0.20, 0.62); Small
Mental	p = 0.73; ES = -0.08 (-0.29, 0.13); Trivial	p < 0.01; ES = 0.51 (0.31, 0.72); Small	p < 0.01; ES = -0.52 (-0.72, -0.31); Small
Performance	p = 0.52; ES = -0.11 (-0.32, 0.09); Trivial	p < 0.01; ES = -0.39 (-0.60, -0.18); Small	p = 0.04; ES = 0.25 (0.05, 0.46); Small
Physical	p < 0.01; ES = -0.96 (-1.17, -0.75); Large	p < 0.01; ES = 0.71 (0.51, 0.92); Moderate	p < 0.01; ES = -1.44 (-1.64, -1.23); Large
Temporal	p < 0.01; ES = -0.76 (-0.96, -0.55); Moderate	p = 0.75; ES = 0.08 (-0.13, 0.28); Trivial	p < 0.01; ES = -0.72 (-0.92, -0.51); Moderate
Tactical and Technical Demands			
Total involvements	p < 0.01; ES = -0.71 (-0.88, -0.55); Moderate	p = 0.86; ES = 0.04 (-0.12, 0.21); Trivial	p < 0.01; ES = -0.63 (-0.79, -0.46); Moderate
Successful pass	p < 0.01; ES = -0.69 (-0.86, -0.53); Moderate	p = 0.04; ES = 0.2 (0.04, 0.37); Small	p < 0.01; ES = -0.74 (-0.91, -0.58); Moderate
Unsuccessful pass	p = 0.28; ES = -0.13 (-0.29, 0.04); Trivial	p = 0.24; ES = 0.14 (-0.03, 0.3); Trivial	p = 0.04; ES = -0.2 (-0.37, -0.04); Small
Successful catch	p < 0.01; ES = -0.61 (-0.77, -0.44); Moderate	p = 0.02; ES = 0.23 (0.07, 0.4); Small	p < 0.01; ES = -0.68 (-0.84, -0.52); Moderate
Unsuccessful catch	p = 0.64; ES = -0.08 (-0.24, 0.09); Trivial	p = 0.90; ES = 0.04 (-0.13, 0.2); Trivial	p = 0.53; ES = -0.09 (-0.25, 0.07); Trivial
Touches	p = 0.01; ES = -0.25 (-0.42, -0.09); Small	p = 0.95; ES = -0.03 (-0.19, 0.14); Trivial	p = 0.07; ES = -0.18 (-0.35, -0.02); Trivial
Passes per touch	p = 0.17; ES = -0.15 (-0.31, 0.01); Trivial	p = 0.51; ES = 0.09 (-0.07, 0.26); Trivial	p = 0.06; ES = -0.19 (-0.36, -0.03); Trivial

Data are Cohens d effect size ± 95% CI; -ive values indicate results favour left side condition.

Table 7.6. Effect of differences in pitch size on subjective task-load and tactical and technical demands.

Field size	Small × Medium	Medium × Large	Small × Large
Player number	6 vs. 6	6 vs. 6	6 vs. 6
Subjective Task-load			
Effort	p = 0.94; ES = 0.04 (-0.2, 0.28); Trivial	p = 0.16; ES = 0.22 (-0.02, 0.46); Small	p = 0.15; ES = 0.23 (-0.01, 0.47); Small
Frustration	p = 0.99; ES = 0.02 (-0.22, 0.25); Unclear	p = 0.97; ES = -0.03 (-0.27, 0.21); Unclear	p = 0.99; ES = -0.01 (-0.25, 0.23); Unclear
Mental	p = 0.81; ES = -0.08 (-0.31, 0.16); Trivial	p = 0.51; ES = 0.14 (-0.1, 0.37); Trivial	p = 0.90; ES = 0.05 (-0.19, 0.29); Trivial
Performance	p = 0.19; ES = 0.21 (-0.03, 0.45); Small	p = 0.01; ES = -0.36 (-0.6, -0.12); Small	p = 0.54; ES = -0.13 (-0.37, 0.11); Trivial
Physical	p = 0.65; ES = 0.11 (-0.13, 0.34); Trivial	p = 0.43; ES = 0.15 (-0.09, 0.39); Trivial	p = 0.15; ES = 0.23 (-0.01, 0.47); Small
Temporal	p = 0.94; ES = 0.04 (-0.2, 0.28); Trivial	p = 0.62; ES = -0.11 (-0.35, 0.12); Trivial	p = 0.06; ES = 0.28 (0.04, 0.52); Small
Tactical and Technical Demands			
Total involvements	p < 0.01; ES = -0.3 (-0.46, -0.14); Small	p = 0.44; ES = 0.1 (-0.06, 0.26); Trivial	p = 0.16; ES = -0.15 (-0.31, 0.01); Trivial
Successful pass	p = 0.65; ES = -0.07 (-0.24, 0.09); Trivial	p = 0.06; ES = 0.19 (0.03, 0.35); Trivial	p = 0.54; ES = 0.09 (-0.08, 0.25); Trivial
Unsuccessful pass	p = 0.88; ES = -0.04 (-0.2, 0.12); Trivial	p = 0.45; ES = -0.1 (-0.26, 0.06); Trivial	p = 0.36; ES = -0.11 (-0.27, 0.05); Trivial
Successful catch	p = 0.07; ES = -0.18 (-0.35, -0.02); Trivial	p = 0.98; ES = 0.02 (-0.14, 0.18); Trivial	p = 0.27; ES = -0.13 (-0.29, 0.03); Trivial
Unsuccessful catch	p = 0.09; ES = -0.17 (-0.34, -0.01); Trivial	p = 0.99; ES = 0.01 (-0.15, 0.18); Trivial	p = 0.35; ES = -0.11 (-0.28, 0.05); Trivial
Touches	p = 0.03; ES = -0.21 (-0.37, -0.05); Small	p = 0.98; ES = -0.02 (-0.18, 0.15); Trivial	p = 0.09; ES = -0.17 (-0.34, -0.01); Trivial
Passes per touch	p = 0.30; ES = 0.12 (-0.04, 0.28); Trivial	p = 0.97; ES = 0.02 (-0.14, 0.18); Trivial	p = 0.33; ES = 0.12 (-0.04, 0.28); Trivial

Data are Cohens d effect size ± 95% CI; -ive values indicate results favour left side condition.

7.4 Discussion

This study investigated the variability of physical, technical, and subjective task-load demands in SSG, and the effect of manipulation of pitch size and player numbers in SSG on the physical, technical, and subjective task-load demands in adolescent Rugby Union players during an on-side touch game. When the same games were repeated there was high variability in the technical demands (CV > 10%), and in the performance (CV = 12.50%) and frustration (CV = 17.65%) subscales for subjective task-load, as well as for distances travelled at high velocities (≥60% MAS) (CV Range = 16.09% to 51.18%). Heart rate responses (CV < 4.28%), and low speed movements (CV = 5.24%) had much lower variability between the test and re-test conditions. Reducing the number of players increased movement demands such as m/min (ES range = 0.45 to 1.45) and technical exposures such as total involvements (ES Range = 0.04 to 0.63). Increasing the size of the pitch increased movements demands but had no effect for technical demands. These results indicate that alteration of player density can influence physical demands, through either pitch size or play number manipulation, however, only player numbers will influence technical exposures. Further, there were trivial to small changes in subjective task-load for manipulating pitch size. Trivial to large changes for player numbers were observed, with large increases seen for physical (ES =0.8; 95%CI 0.59 to 1.01) and performance (ES = 1.44; 95%CI 1.64 to 1.23) task-loads, when comparing the 4 vs. 4 and 12 vs. 12 conditions. These results show that pitch size and player number manipulation differentially influence the physical, technical, and subjective task-load demands in adolescent Rugby Union players.

Player movements increased in games with lower player density, for example, variables such as distance >30% ASR increasing by three times across condition. This study supports previous research that has shown greater external demands when pitch size is increased and player numbers are decreased [42]. While there were clear changes for external demands and sRPE, HR responses showed no obvious pattern to constraint manipulation. The inconsistent HR response may be due to the limitations of HR in assessing intermittent team sports activities, as heart rate can respond slowly to changes in work rate and is influenced by individual constraints such as hydration status [60, 263]. Although the conditions were performed in standardised conditions, no pre-testing assessments on variables such as hydration were conducted. These results may indicate that HR is not unidirectionally influenced by pitch size or player number, consistent with previous research, potentially limiting the usefulness of HR by practitioners to monitor the demands of SSG [238].

The only movement variable that favoured high player numbers, and smaller pitches was low intensity distance (<60% MAS), which was at walking pace (≤ 2.3 m$\cdot$s^{-1}). Findings showed that subjects reached a greater %VMAX in SSG that had lower player density. For example, players in the 4 vs. 4 and 12 vs. 12 condition achieved an average of 86% (range = 75 - 97%), and 74% (range = 61 - 97%) of maximum velocity, respectively. This is the first study to quantify how task constraint manipulation influences the %VMAX achieved during SSG in Rugby Union [42]. Understanding the %VMAX achieved is important as previous research in elite Australian Rules football has demonstrated that both an excessive and insufficient number of exposures to sprinting velocities greater than 85% of maximum velocity may be a risk factor for injury [264].

Total acceleration demands were influenced by player number manipulation, but not pitch size. Specifically, it was found that decreasing player numbers increased the overall acceleration demands by ~19%. Previously research has been shown that reducing the pitch size will emphasise acceleration and deceleration [40]. Despite this, results show there was no effect of pitch size on total acceleration demands. However, this is the first study to report the effect of constraint manipulation in SSG on acceleration density index, a metric that represents the ratio between acceleration load and total distance (i.e., acceleration load per 10 m) [42, 253]. The results show that on a smaller pitch, or with greater number of players, the acceleration density index increases, indicating a greater emphasis on acceleration over distance. These findings can have practical importance when programming SSG for different session objectives to alter the emphasis of training, such as prescribing games with smaller pitch sizes, or with greater player numbers on training days where limiting total distance but maintaining acceleration demands is desired [40].

The use of SSG to facilitate technical development may be beneficial as athletes are exposed to technical demands in an open environment, which is more ecologically valid than closed, repetitive practice and therefore may increase transfer [265]. Technical demands had high variability (CV > 10%), where previous research has reported inconsistent findings, with both high and low variability being reported [244, 245]. This study found that the technical involvements, such as total involvements and passes, increased as player numbers were reduced, while pitch size had trivial effects. These findings are consistent with previous research in rugby league [85]. Therefore, to increase the exposure to technical actions and potentially improve skill acquisition, coaches may wish to reduce the numbers of players in their SSG, while still maintaining semblance of the sport to promote skill transfer [243]. However, further research is required to understand the chronic effect of different SSG on the development of technical skills in adolescent Rugby Union players.

Subjective task-load demands can be altered through the manipulation of player numbers during SSG. Lower player numbers causing small to large increases effort, and moderate increases for temporal demands were observed for both 6 vs. 6 and 4 vs. 4 conditions compared to 12 vs. 12. Previous research has demonstrated that SSG constraints can be deliberately manipulated to target various subjective task-loads, by altering rules of the game without the knowledge of the participants, deliberately making poor officiating decisions, and playing offside rules [94]. Understanding task-load may be useful as high cognitive effort has previously been associated with improved motor learning outcomes in sport [266]. Consequently, practitioners should consider the subjective task-load demands, for example reducing player numbers to increase effort, in conjunction with the physical and technical demands when manipulating SSG, as this may support skill development.

There are some limitations to this study that may influence the applicability of the results. First, isolated measures of technical demands were used, which did not encompass all the technical and/or tactical actions an individual may perform within a game. For example, actions that build defensive pressure, such as line speed, were not recorded. Such defensive actions would likely have a material effect on the actions of the attacking team, as defensive pressure has been found to influence attacking skill execution in female rugby 7's [267]. Therefore, the results in relation to technical demands should not be viewed as a complete account of all technical or tactical actions. Additionally, no information was collected concerning the state of physical or psychological readiness prior to the SSG. Whilst subjects were asked to refrain from physical activity prior to the sessions, the population involved was schoolboy athletes. Consequently school-based activities, such as physical education classes, or examinations, may have influenced readiness prior to the SSG. Finally, no a-priori sample size calculation was performed. The sample size was a convenience sample, based on the logistics of the study. This justification (i.e., resource constraint) is a valid method of determining sample size in applied research [268]. Future research should examine the implications of constraint manipulation, such as how constraints may effect subsequent fatigue, or physiological and/or technical adaptations to assist coaches in understanding how to effectively prescribe SSG.

7.5 Conclusion

This is the first study to investigate the effect of manipulating player numbers on a number of novel metrics, such as subjective task load, %VMAX, and acceleration density index in adolescent Rugby Union players. Findings show there is high variability in the technical exposures, distance travelled at >60% MAS and the performance and frustration subscales when games were repeated with identical task constraints. Overall, SSG with reduced player numbers have greater physical, technical, and effort and temporal demands. Further, SSG played on larger pitches had generally greater physical and temporal demands. However, there was no effect on technical demands. Additionally, manipulating pitch size did not change acceleration demands. Therefore, as a consequence of the substantial differences in demands placed on the athletes, it is strongly advised when designing SSG that pitch size and player numbers are manipulated to align to the specific aims of the training session.

7.6 Practical applications

Increasing the pitch size or reducing the number of players on the pitch will increase movement demands. Increasing movement demands may be desirable at different points throughout the season or playing week. For example, in the pre-season the development of physical capacity, such as aerobic fitness, is emphasised. Additionally, higher movement demands may be desirable during the in-season period early in the training week, to allow for adequate recovery prior to the following game. In training sessions closer to game day, it could be recommended that SSG should be played on smaller pitch sizes and with higher player numbers. Increasing player density will reduce the movement demands and subsequent physical fatigue. SSG can be manipulated to increase technical exposures by reducing player numbers. The development of sports-specific skills is a key element of long-term athletic development. Therefore, coaches of adolescent athletes should reduce player numbers, such as utilising 4 vs. 4 as opposed to 6 vs. 6 or 12 vs. 12, in their small-sided games to facilitate a greater number of technical exposures. This study used technology that may not be easily accessible in youth sporting environments, however, the findings are applicable without the use of such technology. Coaches should be mindful that this study investigated pitch sizes between 750m^2 and 1750m^2, with between eight and 24 players in each game. Extrapolating the results of this study beyond these bounds may reduce the applicability of the findings.

Chapter 8. Final Discussions

The aim of adolescent athletic development is to "develop healthy, capable, and resilient young athletes, while attaining widespread, inclusive, sustainable, and enjoyable participation for athletes of all levels" [5]. For some adolescent athletes, partaking in sport is a social activity, whereby enjoyment and participation are the primary outcomes. However, some adolescent athletes, have the desire to perform at the highest level [8]. This creates a complex adolescent development environment, with four key challenges being previously proposed [5]:

1) Scheduling tug of war [23].
2) Chaotic, variable training loads [24].
3) Coach-athlete mismatch [25].
4) Misalignment between academics and sporting pursuits [26].

These four key challenges can cause significant negative effects on the adolescent athlete if not properly managed. For example, adolescent athletes are prone to outcomes such as burnout, non-functional over reaching and sustaining overuse injuries when training is improperly managed [269]. These challenges become emphasized in athletes who specialise in certain sports or aim to compete at higher levels [270, 271]. This thesis focussed on adding to the knowledge base and providing a more complete understanding of the chaotic, and highly variable training loads of adolescent Rugby Union plaers. Throughout this thesis all four of the aforementioned challenges became apparent, in addition to further challenges, demonstrating they are constantly interwoven into the adolescent performance environment. The findings of this thesis can add additional information as to the training of adolescent Rugby Union players to the framework proposed by Scantlebury et al., [5], and introduced in Chapter 1 (Figure 8.1).

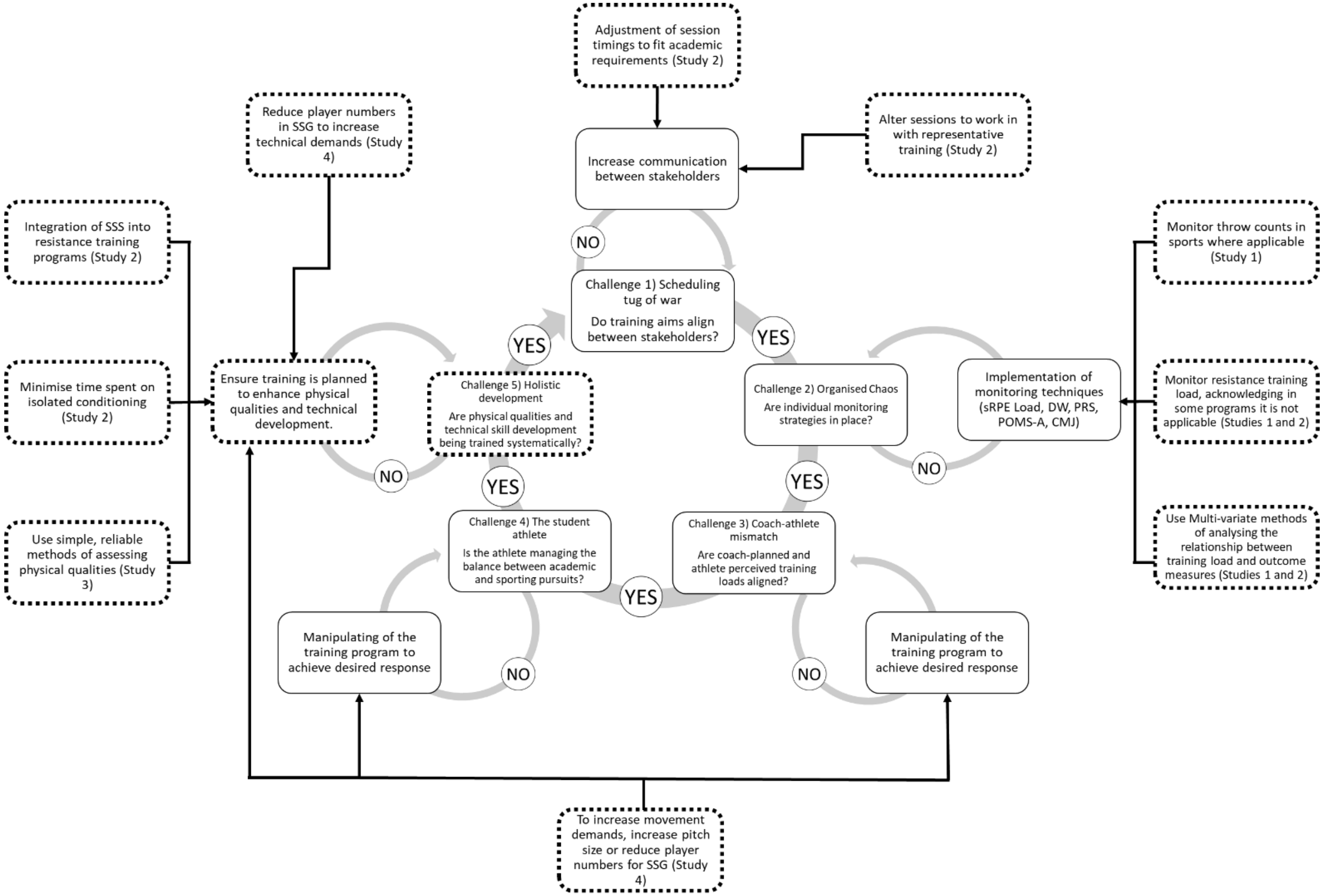

Figure 8.1. Updated framework demonstrating the complexity of adolescent athletic development [5]. - - - indicates additional contributions to knowledge arising from this thesis. SSS = Sports specific skills, SSG = Small-sided games.

This thesis investigated the assessment and manipulation of training practices in adolescent athletes. Whilst training practices have been previously investigated, often research has separated and compartmentalised different elements of training, leading to an incomplete picture of the holistic demands placed on adolescent athletes [23, 31, 32, 56, 116]. Additionally, previous research has also indicated that there is a large variation in the training demands placed on athletes, and therefore investigation into the athletic practices specific to the industry partner for this thesis was warranted.

Study one investigated the commonly reported methods of assessing training load, and their relationship to outcome measures such as change in physical qualities, injury, or illness, via a systematic review and best evidence synthesis. The information from study one, combined with the industry partner's current practices, informed the methodology in study two. Study two was an observational study that detailed the training demands of adolescent Rugby Union players and their relationship to changes in physical qualities. To validate and assess the reliability of the methodology used in study two, study three examined the effect of grip on the validity and reliability of outcome variables for the isometric midthigh pull. The results of study two demonstrated that a significant portion of training time was dedicated to SSG. To improve the prescription of SSG, study four investigated the effect of manipulating task constraints on the technical, physical, and subjective task loads of adolescent Rugby Union players. The aims, primary findings and practical applications of this thesis are summarised in Table 8.1.

Table 8.1. Summary of study aims, primary findings, and practical applications

Aims	Primary Findings	Practical applications
***Study one.* Methods of monitoring internal and external loads and their relationship with changes in physical qualities, injury and illness**		
1) Systematically examine the methods of reporting internal and external loads in adolescent athletes 2) Describe their relationship with changes in physical qualities, injury, or illness.	a) The most common methods of monitoring internal load in adolescent athletes are sRPE and heart rate, whilst the most common methods of monitoring external load are training duration and global navigation satellite systems. b) There is moderate evidence of a relationship between resistance training volume and increases in strength. c) There is moderate evidence of a relationship between training duration and throw count and injuries. d) All other relationships between internal and external loads and changes in physical qualities, injuries, and illness were limited or inconsistent.	i. Resistance training volume load should be considered when monitoring strength training. ii. Throw or pitch count should be monitored in sports where it is applicable. iii. Multi-variate methods of analysing the relationship between training load and outcome measures should be used.
***Study two.* Training demands in adolescent athletes and relationship to changes in physical qualities**		
1) Quantify the training loads, both field and resistance training, in adolescent rugby players. 2) Quantify the changes in levels of stress and recovery of athletes throughout the pre-season period. 3) Assess the degree of multicollinearity in training load data. 4) Assess the relationship between training loads and changes in physical qualities in adolescent rugby players.	a) Adolescent athletes may have higher training frequencies, and levels of strength and aerobic fitness than previously reported. b) Significant improvements in aerobic fitness were seen, despite only 6% of training time being spent on conditioning. c) There were no significant changes in levels of stress or recovery. d) There is a high degree of multicollinearity in training load data.	i. Resistance training volume load may be difficult to calculate, dependent on exercise prescription. ii. Sports-specific skills should be incorporated into resistance training sessions, with no negative outcomes on change in physical qualities. iii. Coaches can improve aerobic fitness, whilst minimising time spent on conditioning. iv. Dimension reduction techniques should be considered when assessing the relationship

	e) Number of full body exercises has the greatest relationship to changes in physical qualities.	between training load and outcome measures. v. Coaches should prescribe full body exercises.
***Study three.* Effect of isometric midthigh pull grip on the validity and reliability of outcome variables.**		
1) Quantify the validity of figure eight wraps and bare hand grip (practical measures) compared to strapped and taped grip (criterion) on outcome measures. 2) Examine the reliability of these methods.	a) Bare hands reduced peak force values. b) All conditions had acceptable reliability for peak force. c) All time-bound measures were found to have poor reliability.	i. Peak force can be reliably assessed using bare hands, straps and tape or figure eight straps. ii. Bare hands will reduce peak force, may not be appropriate when attempting to accurately assess maximal whole body isometric force production. iii. Practitioners should not use different methods of gripping the bar interchangeably and it is recommended that either straps and tape or figure eight straps should be used.
***Study four.* Effect of pitch size and player number manipulation on the physical, technical, and subjective task-load demands in small-sided games.**		
1) Assess the variability of physical, technical, and subjective task-load demands in SSG. 2) Assess the effect of manipulation of pitch size and player numbers in SSG on the physical, technical, and subjective task-load demands.	a) High variability existed for technical demands, the performance and frustration sub-scales, and distance travelled at high velocities. b) Heart rate responses and low-speed movements had lower variability. c) Reducing player numbers increased movement and technical demands. d) Increasing pitch size increased movement demands but did not affect technical demands. e) Subjective task load will change when manipulating pitch size and player numbers.	i. To increase movement demands, coaches should increase pitch size, or reduce player numbers. ii. To increase technical demands, coaches should reduce player numbers. iii. As development of sports-specific skills is a key element of long-term athletic development, coaches of adolescent athletes should reduce player numbers in SSG.

8.1 Monitoring and assessment in adolescent athletes

The competing demands that adolescent athletes face mean that monitoring these demands in their entirety may be of value for practitioners and organisations (such as schools) that are required to develop adolescents across a range of areas. The findings of studies one and two make additional contributions to the existing knowledge regarding the training practices of adolescent athletes, highlighting the complexities of both resistance and field-based load monitoring. Whilst many of the challenges involved in load monitoring are present across athletes of all ages, they are amplified in adolescent athletes, often due to factors such as competing sporting and social schedules and academic responsibilities [5]. This section will highlight some of the complexities of monitoring the training practices of adolescent athletes that were evident throughout the thesis and how this adds to the existing body of knowledge.

The results of the systematic review and best evidence synthesis (study one) demonstrated that resistance training volume load had moderate relationships with changes in strength. However, the findings of study two demonstrate that it may not always be appropriate to use volume load as the primary method to monitor resistance training due to limitations in its application as it did not capture the load of 43% of exercises included. Previous research investigating volume load in adolescent athletes has also excluded exercises that were isolation exercises, or used a pulley system or counterbalancing, however the amount of exercises that were excluded were not reported [31]. Examples of exercises that were removed from analysis in study two include sled pushes, isometrics (e.g., planks), or counterbalanced exercises (e.g., landmine exercises). Therefore, volume load was removed from analysis, as it only represented a small portion of the actual load performed. Given volume load was recommended in study one, but found to not be applicable in study two, practitioners need to consider the appropriateness of their load monitoring tools depending upon their environment and programming style. For example, volume load may be useful in weightlifting or powerlifting sports.

In this thesis, two different methods of assessing running load were used. In study two, absolute velocity zones (Walking (<3 m.s^{-1}), Jogging (3 – 5 m.s^{-1}), Running (5 – 7 m.s^{-1}), Sprinting (>7 m.s^{-1})) were used to assess running demands. However, in study three, relative velocity zones were used to assess the running demands of SSG (<60% MAS, 60-79% MAS, 80 – 99% MAS, 100% MAS – 29% ASR, and >30% ASR [272]). This adjustment was in part due to the observational nature of study two, as there were no changes to the processes already in place at the industry partner. Previously, it has been demonstrated that the use of arbitrary speed thresholds is likely to inaccurately estimate the workloads performed [251]. Whilst not directly examined, it is likely that arbitrary thresholds would inaccurately assess high-speed running, with recorded MAS ranging from 3.17 to 4.96 across all subjects. Therefore, using relative bands were thought to provide a more accurate representation of the training load in adolescent athletes, due to their highly varied levels of aerobic fitness.

In studies two and four of this thesis, the physical qualities of adolescent Rugby Union players were reported. The subjects within study two (mean age ± SD: 17.2 ± 0.7 years) were of a similar age to those previously reported in schoolboy Rugby Union (mean age ± SD: 16.9 ± 0.4 years) [17, 31], however, had greater bodyweight (mean mass ± SD: 80.1 ± 10.5 vs. 87.0 ± 11.6 kg) [17, 31]. Interestingly , the bodyweights were similar to those previously reported in academy Rugby Union players (mean mass ± SD: 88.3 ± 11.9 kg) [17, 31]. Further, bench press 1RM was greater than those previously reported in both schoolboy and academy athletes (Mean 1RM ± SD: 106.23 ± 14.30 vs. Mean 3RM ± SD: 68.5 ± 12.8 (schoolboy) vs. 82.6 ± 10.8 kg (academy)) [17, 31]. Inconsistencies in methods of assessing CMJ height, sprint timing, and aerobic fitness make it difficult to compare physical qualities between studies [17, 31, 102]. One of the reasons for the discrepancy in physical qualities between the studies in this thesis and previous research, may be the progressive strength and conditioning program, implemented by the industry partner, for athletes as young as 12 years old. Whilst the training environment in previous studies cannot be assumed, it is recommended that progressive strength and conditioning programs be implemented to ensure development of physical qualities that underpin sporting tasks and are integral to long term athletic development.

Study three examined the validity and reliability of different grip methods in the performance of the IMTP. This study was performed to validate the methodology used in study two and assist practitioners in improving the efficiency of testing for an assessment that is widely used [273-275]. Further, the industry partner was intending to implement the IMTP into training squads beyond the senior programs as part of a school-wide testing regime. The IMTP was being proposed as it is perceived to be a low-skill, and safe method of assessing maximal force output [37]. However, due to the time-consuming nature of the recommended guidelines for testing using the IMTP (i.e., using straps and then tapping individuals onto the bar), more practical methods of performing the IMTP were required to increase the efficiency of testing. But, whilst the use of figure eight straps did demonstrate good validity and reliability for peak force, no other metrics were reliable.

Despite commonly being proposed as a time efficient method of strength testing, the IMTP was observed to be impractical in group settings with time constraints as the stringent testing protocols (e.g., stable baseline, no countermovement) are often not adhered to [37]. Further, it should be acknowledged that only one athlete can perform the IMTP at any point in time, due to the procurement of multiple force plates often being financially prohibitive. As such, it is not recommended that the IMTP be adopted as an assessment of strength in group-based, resources poor, adolescent environments, such as schools, as the depth of reliable information obtained (i.e., only peak force) does not offset the limitations of the assessment. However, the IMTP may be useful in settings such as one on one coaching, or if resources, such as time, staff, and finances, are abundantly available. Practitioners working with adolescent athletes who do not possess the technical competence to safely execute testing with traditional strength exercises, may be advised to focus on technical development as opposed to assessing physical qualities.

8.2 Small-sided games

The results of study two demonstrated that a significant portion of training time was dedicated to game-based drills (i.e., SSG). These types of drills are widely used within adolescent sport for a variety of reasons including to support the development of both physical, technical and, at times, tactical capabilities [42]. Further, SSG are often an efficient use of scarce resources, such as time, playing space and player number, and are an enjoyable method of training. As such, study four investigated the effect of pitch size and player number manipulation on the technical, physical and subjective task load demands in adolescent Rugby Union players. Therefore, developing an understanding of how common constraints influence the demands placed on athletes will allow for more accurate training prescriptions.

While the effect of manipulating task constraints on the physical demands of SSG have been extensively investigated [42], study four had a number of novel elements that assist in it contributing to the broader scientific literature. These include:

i. Reporting of less common, but important, metrics such as percentage of maximum velocity achieved and acceleration density index. These GNSS metrics will assist practitioners in understanding how to manipulate SSG to achieve training outcomes at various points in the macro and mesocycles. Details of these metrics are provided in study four.
ii. Reporting of the variability in the technical, physical, and subjective task-load demands in adolescent athletes. This information will assist both practitioners and researchers in understanding the highly variable load adolescent athletes may experience, even under identical task constraints.
iii. Use of Rugby Union players, and rules specific to Rugby Union. Previous literature has focussed on rugby league, or used alternate rules such as offside touch [42].
iv. Reporting of the change in subjective task-load as a byproduct of constraint manipulation. Previous literature has only demonstrated changes in subjective task load when deliberately targeted by task constraint manipulation [94].

8.3 Limitations

There were several limitations in the studies conducted throughout this thesis. However, most of the limitations were due to the practicalities of working with adolescent athletes in an applied environment and unlikely to be limited to the studies within this thesis. While the limitations of each study were detailed in the relevant chapter, a summary of the limitations of each study is included below:

Study one

1. The best-evidence synthesis used a “vote-counting” methodology. This methodology was used as there is no standardised method of assessing the magnitude of load.

Study two

2. Data collection was influenced by natural disasters, and the COVID pandemic. This influenced two weeks of data collection, where training was either cancelled or altered.
3. Academic requirements dictated that the pre- and post- testing session times were different. Pre-testing was conducted at 06:00am and post-testing was conducted at 03:15pm. Diurnal variation has been shown to influence physical qualities such as speed, power, strength, and aerobic fitness [276-278].

Study three

4. The participants were not adolescent athletes. This was due to it being impractical to conduct the study on adolescent athletes due to lack of availability of required gym space, and highly chaotic scheduling of the athletes, reducing the windows whereby reliability testing was appropriate. Given this, it was decided in conjunction with the industry partner that an alternate sample should be used. Previously it has been demonstrated that subjects with six months resistance training are shown to have acceptable reliability for strength testing [222]. Therefore, the results of study three were generalised to the athletes in study two, who all had >6 months resistance training experience. However, the reliability of strength measures can differ between maturity groups [227]. Therefore, whilst the athletes in study two were resistance trained, caution should be used when generalising the results of study three to a youth population.

Study four

5. A direct assessment of maximal heart rate was not performed. As such, internal measures of load, such as TRIMP, and TRIMP variations could not be accurately determined [279].
6. Throughout the testing, on three occasions, subjects assigned to a team did not attend the testing session. Given the study was team-based, an alternative, MAS-matched subject was assigned to replace the missing subject.

8.4 Future directions

This thesis has investigated the assessment and manipulation of training practices in adolescent athletes. The findings from this thesis will assist practitioners to develop a greater understanding of how to monitor training load in the highly chaotic environment of adolescent athletic development. However, further research is still required in adolescent athletes. The challenges of adolescent athletic development also present unique challenges to conducting high quality research. For example, having athletes complete numerous training programs, across multiple teams, clubs and often sports, makes it difficult to conduct training studies to examine the efficacy of different training protocols. Therefore, future research needs to acknowledge the challenges faced by adolescent athletes and incorporate them into the study design. For example, future research may wish to investigate elements of adolescent athletic development such as the concepts of windows of trainability, that are yet unexplored but often discussed within adolescent literature [1, 2, 201, 280]. However, this research may be best conducted in recreational adolescent athletes, who may be less likely to have highly chaotic training loads.

A key finding of study one, was the common use of logistic and linear regression techniques in establishing the relationship between training load and outcome variables. Study two used a feature selection algorithm to overcome the large degree of multicollinearity in training load data. This technique was selected as the results were perceived to be more interpretable than other, more common methods, such as dimension reduction techniques. However, no research has reported the ease of interpreting the results from different statistical methods. Therefore, future research may consider investigating how easily interpretable the results of different statistical techniques are by strength and conditioning coaches. This information could help to inform researchers as to what technique is appropriate in different circumstances.

Resistance training volume load was found in study one to have moderate relationships to changes in levels of strength. However, in study two, it was demonstrated that resistance training volume load was not applicable for a large number of strength training exercises, such as sleds, cable pulleys, and counterbalanced (i.e., landmine) exercises. Therefore, future research may explore the efficacy of alternative methods of quantifying the load of resistance training exercises in adolescent athletes.

One of the focus areas of this thesis was to investigate the demands of adolescent athletes from both a physical and technical perspective. While this thesis documented the distribution of training load between different training and drill modalities and with different constraints, the chronic effects of these different distributions of training are not known. For example, the effect of increasing the time of field-based training and reducing resistance training has not been investigated. Therefore, future research may look to investigate how training should be distributed in adolescent athletes.

There was evidence in this thesis of the need to manipulate training and testing sessions to accommodate stakeholders (i.e., representative teams) and academic requirements. This is generally perceived to be positive, and indicative of a forward-thinking adolescent development program, with an athlete-centred approach [5]. However, there is no research demonstrating how constantly adjusting schedules influence the outcome for adolescent development, from both a technical and physical standpoint. For example, athletes who compete in multiple sports across various seasons may never have the opportunity to have an “off-season” where physical development, and rest and recovery are prioritised. Further, it has previously been demonstrated that high volumes of match-play (i.e., three matches per week) will reduce the amount of training adolescent athletes perform [56]. If field-based training is consistently being compromised due to fatigue from other training, either with alternative sports or resistance training, there will be an effect on the amount of exposure, and therefore development, the athlete has to the technical demands of the game. Conversely, if resistance training is constantly being compromised by excessive field-based training volumes, adolescent athletes may not develop the physical qualities required for their sport. Therefore, future research should investigate as to how to best manage the compromise between stakeholders to ensure that there is balance in adolescent athletes training programs.

Study four demonstrated the effect of task constraint manipulation during SSG on the acute demands placed on adolescent athletes. Future research should examine the short- and long-term implications of these findings. For example, it was proposed that manipulating task constraints to reduce physical demands may be more appropriate for athletes closer to game-day. However, it is unknown to what extent manipulating task constraints changes the magnitude of fatigue. Additionally, the chronic effect of performing SSG under different task constraints on technical development and physical adaptations is not yet known. It was also demonstrated that manipulating pitch size altered metrics such as the ADI. This is relevant due to teams commonly theming sessions as being acceleration or running based [40].

Future research may wish to quantify how different themed sessions throughout a training week may affect match day performance.

8.5 Conclusions

This thesis investigated different methods to assess and manipulate training practices in adolescent athletes. A series of four studies were conducted as part of this PhD that have contributed to the body of knowledge regarding the training of adolescent athletes. Specifically, this thesis has focussed on the chaotic, variable training loads that adolescent athlete experience. Additionally, this thesis encountered other challenges that are common to adolescent athletes, such as competing academic requirements and competing training schedules. The findings of this thesis demonstrated that whilst resistance training volume load may have moderate correlations to changes in strength, it is not an appropriate load monitoring tool in all adolescent monitoring programs, as it is not relevant for a significant number of resistance training exercises. Additionally, adolescent Rugby Union players may have greater training frequency, and physical qualities than previously reported, which may be reflective of the continued development of adolescent athletes and growing integration of strength and condition programs with youth in recent years. While the IMTP can be used to assess peak force, using either straps and tape or figure eight straps, time-bound metrics should not be used as they are unreliable. This thesis also demonstrated a significant portion of training is dedicated to game-based drills. Study four found large variability in the physical, technical, and subjective-task load demands of SSG. Further, manipulation of constraints such as pitch size and player numbers may assist coaches in being more precise with training prescription.

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Appendix 1 – List of publications

List of publications relevant to this thesis

1. Dudley C, Johnston R, Jones B, Till K, Westbrook H, Weakley J. Methods of monitoring internal and external loads and their relationships with physical qualities, injury, or illness in adolescent athletes: A systematic review and best-evidence synthesis. Sports Medicine. 53, 1559–1593 (2023). https://doi.org/10.1007/s40279-023-01844-x

I acknowledge that my contribution to the above paper is 85% percent

Charles Dudley ________________ 19/12/2023

I acknowledge that my contribution to the above paper is 3% percent

Richard Johnston ________________ 19/12/2023

I acknowledge that my contribution to the above paper is 2% percent

Ben Jones ________________ 19/12/2023

I acknowledge that my contribution to the above paper is 2% percent

Kevin Till ________________ 19/12/2023

I acknowledge that my contribution to the above paper is 3% percent

Harrison Westbrook ________________ 19/12/2023

I acknowledge that my contribution to the above paper is 5% percent

Jonathon Weakley ________________ 19/12/2023

2. Dudley C, Johnston R, Westbrook H, Weakley J. Training practices of adolescent athletes and relationship to change in physical qualities. Journal of Australian Strength and Conditioning (*in press*).

I acknowledge that my contribution to the above paper is 85% percent

Charles Dudley ___________________ 19/12/2023

I acknowledge that my contribution to the above paper is 5% percent

Richard Johnston ___________________ 19/12/2023

I acknowledge that my contribution to the above paper is 5% percent

Harrison Westbrook ___________________ 19/12/2023

I acknowledge that my contribution to the above paper is 5% percent

Jonathon Weakley ___________________ 19/12/2023

Peter Currell <petercurrell@strengthandconditioning.org>
Thu 31/08/2023 11:31 AM
To: Charles Dudley <Charles.dudley@outlook.com.au>
Hi Charles,

Thank you for submitting your revised article, and I am pleased to let you know this has been accepted for publication. We aim to publish all accepted articles within 12 months, and we will notify you prior to your article being selected for a specific issue of the JASC.

Thank you for your contribution to the JASC, and please let me know if there is anything else we can assist with.

Peter Currell
General Manager
+61 7 55026911
www.strengthandconditioning.org

3. Dudley C, Johnston R, Jones B, Hacking T, McCafferty R, Weakley J. Effect of pitch size and player number manipulation on the physical, technical, and subjective task-load demands in small-sided games. International Journal of Sports Science and Coaching (*in press*).

I acknowledge that my contribution to the above paper is 85% percent

Charles Dudley __________________ 19/12/2023

I acknowledge that my contribution to the above paper is 3% percent

Richard Johnston __________________ 19/12/2023

I acknowledge that my contribution to the above paper is 2% percent

Ben Jones __________________ 19/12/2023

I acknowledge that my contribution to the above paper is 2% percent

Trent Hacking __________________ 19/12/2023

I acknowledge that my contribution to the above paper is 4% percent

Robert McCafferty __________________ 19/12/2023

I acknowledge that my contribution to the above paper is 4% percent

Jonathon Weakley __________________ 19/12/2023

Conference Presentation

1. Dudley C, Johnston R, Jones B, Hacking T, McCafferty R, Weakley J. More than just metres – manipulating small-sided games. *Youth Coaches Rugby Forum. 28-29 Jan 2023.*

The above presentation was based on the work in study four. The presentation was completed by Charles Dudley and Robert McCafferty.

Appendix 2 – Ethics

PARTICIPANT INFORMATION LETTER (Study 2)

PROJECT TITLE: Training practices of adolescent athletes and the relationship to changes in physical qualities
APPLICATION NUMBER: (2021-2301)
PRINCIPAL INVESTIGATOR: Dr. Jonathon Weakley
STUDENT RESEARCHER: Mr. Charles Dudley
STUDENT'S DEGREE: Doctor of philosophy

Dear Participant,

You are invited to participate in the research project described below.

What is the project about?

The research project investigates the training practices of adolescent athletes and the relationship between training and change in physical qualities across multiple age groups. This project is being conducted as part of a Doctorate of Philosophy which is a collaboration between St. Joseph's Nudgee College and Australian Catholic University.

The aim of this project is to assess the relationship between training loads, and changes in physical qualities in adolescent athletes. We will quantify both the strength and conditioning and sports-specific training loads of adolescent athletes over their pre-season term and examine the relationship to changes in physical qualities such as strength, speed, and power. Additionally, we will record athletes levels of stress and recovery throughout the observational period, to assess what role these factors may have in the response to training loads.

It is hoped that the results from this project can assist in the prescription of training loads and rest, assisting coaches and Directors of various sports to plan and implement a best practice training model.

Who is undertaking the project?

This project is being conducted by Charles Dudley and will form the basis for the degree of Doctor of Philosophy at Australian Catholic University under the supervision of Dr. Jonathon Weakley. Charles holds a Bachelors of Exercise and Sports Science (Hons), Bachelor of Business (Sports Management) and a Masters of High Performance Sport. Additionally, Charles has a background in strength and conditioning, having held positions at Olympic, academy, school and club level.

Who can take part in the project?

You have received this invitation to participate in this research as your child (or you) have been identified as being in a training squad, that is being targeted for this project. Participants can take part in this research if they are between 12 and 18 years of age, and do not have an injury or other condition that would preclude them from participation in all physical activity.

What will I be asked to do?

This project will occur at St. Josephs Nudgee College and is observational in nature. Participants will complete a battery of fitness tests before and after an observational period, as well as filling out a weekly stress and recovery scale. Participant's training will not otherwise be altered. Physical capacity testing will use common, safe and simple tests designed to measure strength, speed, power and aerobic fitness. These tests will include using equipment such as force plates and timing gates. Then, for the period of observation you will be asked to train whilst wearing a load monitor (either a global navigation satellite system or heart rate monitor) and fill out a short form that assesses how difficult you found each training session. Additionally, your resistance training sessions will be monitored through strength and conditioning software, called TeamBuildr. Teambuildr is already in use for multiple training squads at St. Joseph's Nudgee College. Once a week, you will be asked to fill out a short recovery and stress scale delivered through TeamBuildr, which assesses factors such as physical performance capability, muscular stress and emotional state. All training will be supervised by a qualified coach, as is standard practice.

How much time will the project take?

This project will take place during the normal course of your training over your pre-season period. The period of observation will be one school term. Testing sessions will take between 60 to 90 minutes and will be performed during normal resistance training periods. The weekly short recovery and stress scale takes approximately 1-2 minutes to complete.

Are there any risks associated with participating in this project?

Any project that involves exercise will carry with it some form of risk, such as muscular strains and sprains. To mitigate these risks all participants will complete a warm-up prior to any testing, supervised by a qualified strength and conditioning coach. Additionally, participants are required to have had previous resistance training experience.

What are the benefits of the research project?

Whilst there will be no direct benefits, such as financial compensation, to participate in this study, there will be indirect benefits. Throughout this study we will be able to carefully analyse training to enable greater planning of training loads. Additionally, long term this project will give greater knowledge as to how adolescent athletes respond to training, allowing coaches and directors of sports at Nudgee College to ensure they are delivering a world class program.

Can I withdraw from the study?

Participation in this study is completely voluntary. You are not under any obligation to participate. If you agree to participate, you can withdraw from the study at any time without adverse consequences. If you do decide to withdraw from the study, data collected during resistance training sessions up until that point in time will be kept and utilised for research purposes.

Will anyone else know the results of the project?

The results of this study will be published within a peer-reviewed sport science journal. All published information will not be identifiable. Throughout the period of observation, data collected will be shared with your coaching team, to ensure appropriate prescription of training loads. Additionally, information from this study will be presented to the St. Joseph's Nudgee College activities department.

Will I be able to find out the results of the project?

Once the project is published, you will be able to read the final manuscript.

Who do I contact if I have questions about the project?

Please feel free to contact Mr. Charles Dudley at charles.dudley@myacu.edu.au

What if I have a complaint or any concerns?

The study has been reviewed by the Human Research Ethics Committee at Australian Catholic University (review number 20XX-YYY). If you have any complaints or concerns about the conduct of the project, you may write to the Manager of the Human Research Ethics and Integrity Committee care of the Office of the Deputy Vice Chancellor (Research).

Manager, Ethics and Integrity
c/o Office of the Deputy Vice Chancellor (Research)
Australian Catholic University
North Sydney Campus
PO Box 968
NORTH SYDNEY, NSW 2059
Ph.: 02 9739 2519
Fax: 02 9739 2870
Email: resethics.manager@acu.edu.au

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

I want to participate! How do I sign up?
Both student and parent consent forms can be signed electronically. Please contact Charles at charles.dudley@myacu.edu.au , or come to the activities office if you are interested in participating.

Yours sincerely,

Charles Dudley

Please retain a copy of this information letter

PARTICIPANT INFORMATION LETTER (Study 3)

PROJECT TITLE: Variability in physical capacity in males and females

APPLICATION NUMBER: 2020-1362
PRINCIPAL INVESTIGATOR: Dr Jonathon Weakley

Dear Participant,

You are invited to participate in the research project described below.

What is the project about?
This research project investigates the reliability of commonly used physical tests in both men and women.

Physical capacity across a range of tests (e.g., jump height) is often quantified in sport to help guide practitioners about an athlete's readiness to perform. This testing information is essential for making informed decisions regarding the athletes training load and exposure to match play. However, it is important to consider the error of each test and how performance in each test fluctuates across time. Additionally, it is important to consider how changes in lifestyle may influence these testing results. For example, if an athlete improves their jump performance by 10%, but the error of the test is 12%, then the athlete may not have improved at all. Therefore, quantifying the error associated with commonly used tests of physical capacity in both men and women can support the appropriate interpretation of commonly used tests and help guide the safe prescription of exercise.

It is hoped that this project will help practitioners interpret normal fluctuations in physical capacity and with this information improve exercise prescription.

Who is undertaking the project?
This project is being conducted by Dr Jonathon Weakley and Associate Professor Shona Halson at Australian Catholic University. Jonathon has a BAppSci in Sports Nutrition, a MSc in Nutrition, GCert in Strength and Conditioning, and a PhD in Strength and Conditioning. He has over 50 peer-reviewed publications on the topic of sports performance and has spoken at a number of international conferences on topics relating to strength and conditioning. Associate Professor Shona Halson is a world leader in sports science and has over 200 peer-reviewed manuscripts. She previously held a senior role at the Australian Institute of Sport and is now researching in the topics of Human Performance, Recovery, and Women's Health.

Are there any risks associated with participating in this project?
While the risks in this project are low, as this project involves exercise it is possible injury can occur. To mitigate this risk, participants are required to complete regular exercise (e.g., >2 times per week), have no current injuries, and all participants will complete a warm up prior to completing all procedures. You will not be asked to complete anything that you do not want to complete and you can choose if there are some exercises you do not want to do.

What will I be asked to do?
Participants will be asked to complete 8 testing sessions across a 70-day timeframe. All participants can choose the number of sessions that they would like to attend. Prior to each testing session,

participants will complete a standardised warm up which involves dynamic stretching and exercises that mimic the exercises that will be completed during the testing.

During the first testing session, participants will have all protocols explained and you will be able to choose the exercises that you would like to complete. These will include: countermovement jump, 30cm drop jump, plyometric push up, back squat, bench press, hand dynamometer (i.e., hand squeeze) test, isometric mid-thigh pull, repeated sprint assessment, Yo-Yo IRL1, and sit and reach test. These exercises will involve efforts against a resistance (e.g., hand dynamometer test) or running (e.g., Yo-Yo IRL1). The best attempt at each exercise that you choose will be recorded and compared to efforts on other days. Additionally, during the testing period, you will be provided a sleep watch, thermometer, and free tracking app that allows you to monitor your menstrual cycle.

How much time will the project take?
Each session will take approximately one hour but can take less time if the participant wishes to only complete a small number of tests.

What are the benefits of the research project?
The information from this study will help strength and conditioning practitioners gain a better understanding of normal changes in physical performance. This normal variation can then be used to guide exercise prescription and support the appropriate assessment of physical capacity in humans.

Can I withdraw from the study?
Participation in this study is completely voluntary. You are not under any obligation to participate. If you agree to participate, you can withdraw from the study at any time without adverse consequences. If you do decide to withdraw from the study, data collected during resistance training sessions up until that point in time will be kept and utilised for research purposes.

Will anyone else know the results of the project?
The results of this study will be published within a peer-reviewed sport science journal. All information that is published will not be identifiable and your data will be anonymised immediately.

Will I be able to find out the results of the project?
Yes, your results will be observable immediately post-testing. Furthermore, once the project is published, you will be able to read the final manuscript.

Who do I contact if I have questions about the project?
Please feel free to contact Dr Jonathon Weakley at Jonathon.weakley@acu.edu.au

What if I have a complaint or any concerns?
The study has been reviewed by the Human Research Ethics Committee at Australian Catholic University (review number 2020-1362). If you have any complaints or concerns about the conduct of the project, you may write to the Manager of the Human Research Ethics and Integrity Committee care of the Office of the Deputy Vice Chancellor (Research).

Manager, Ethics and Integrity
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Ph.: 02 9739 2519

Fax: 02 9739 2870
Email: resethics.manager@acu.edu.au

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

I want to participate! How do I sign up?

If you are interested in participating, please feel free to speak to Dr Jonathon Weakley in building 211.1.26. You will be able to ask any further questions and sign a consent form.

Yours sincerely,

Dr Jonathon Weakley

PARTICIPANT INFORMATION LETTER (Study 4)

PROJECT TITLE: Effect of manipulating of playing drills on the physical and technical demands in Football and Rugby small-sided games
APPLICATION NUMBER: (2022-2717)
PRINCIPAL INVESTIGATOR: Dr. Jonathon Weakley
STUDENT RESEARCHER: Mr. Charles Dudley
STUDENT'S DEGREE: Doctor of philosophy

Dear Participant,

You are invited to participate in the research project described below.

What is the project about?

The research project investigates how manipulation of training drills, specifically player numbers and pitch size, influences the physical and technical demands in both Rugby Union and football. This project is being conducted as part of a Doctor of Philosophy which is a collaboration between St. Joseph's Nudgee College and Australian Catholic University.

Coaches use a variety of different training drills to ensure that athletes are adequately prepared for the demands of match play. Every drill has a set of environmental (i.e. pitch size), individual (i.e. fitness level), or task (i.e. rules) constraints, that will impact the physical, tactical and technical element of the drill. Therefore, the aim of this project is to investigate how the manipulation of environmental constraints influences the demands of the drill. This period of investigation will take place over seven training sessions, lasting approximately 45 minutes. During these training sessions, the participants will have their physical qualities, such as speed and aerobic fitness, measured, and will then participate in several small-sided games with various field sizes and pitch numbers. Participants in this study will complete either the football or rugby conditions, based on their primary sport as identified by their Director of Sport.

It is hoped that the results from this project can assist in the prescription of training drills, informing coaches and Directors of sports to plan and implement a best practice training model.

Who is undertaking the project?

This project is being conducted by Charles Dudley and will form the basis for the degree of Doctor of Philosophy at Australian Catholic University under the supervision of Dr. Jonathon Weakley. Charles holds a Bachelors of Exercise and Sports Science (Hons), Bachelor of Business (Sports Management) and a Masters of High-Performance Sport. Additionally, Charles has a background in strength and conditioning, having held positions at Olympic, academy, school and club level. Dr. Jonathon Weakley has over ten years' experience in professional sport and holds a Doctor of Philosophy, focusing on the strength and conditioning practices of adolescent athletes.

Are there potential conflicts of interest?

This project forms part of a funded PhD Scholarship between St Joseph's Nudgee College and ACU. As part of this agreement Charles Dudley works as a strength and conditioning coach at the college. While this may present as a potential conflict of interest, Charles has no influence over factors such as team selection, and as such there is minimal likelihood of coercion.

Who can take part in the project?

You have received this invitation to participate in this research as your child (or you) have been identified as being in a training squad that is appropriate for this project. Participants can take part in this research if they are between 12 and 18 years of age, do not have an injury or other condition that would preclude them from participation small-sided games, and have at least 24 months experience in either Rugby Union or football.

What will I be asked to do?

This project will occur at St. Josephs Nudgee College. This project will investigate two primary variables, being changes in pitch size, and changes in player numbers.

In session one, participants will have physical qualities (speed and fitness) and anthropometrics (seated and standing height, and weight) assessed. This information will be used to facilitate reporting performance for individuals relative to their physical capacities.

The following tests and information will be collected in session 1.

- 40m sprint
- 2km run time trial
- Standing height, seated height and weight
- Date of birth

Following the assessment of physical qualities in session 1, participants will be familiarised with the small-sided games.

In sessions two to seven, participants will take part in a number of small-sided games. Small-sided games will consist of 4 x 3 minute periods, separated by a one minute break. Participants will perform one condition per session. In manipulation of the pitch size, the following sizes will be used; Small = 30m (L) x 25m (W), Medium = 40m (L) x 30m (W), Large = 50m (L) x 35m (W) (Figure 1). In manipulation of player numbers, the following numbers will be used; Small = 4 v 4; Medium = 6 v 6; Large = 12 v 12.

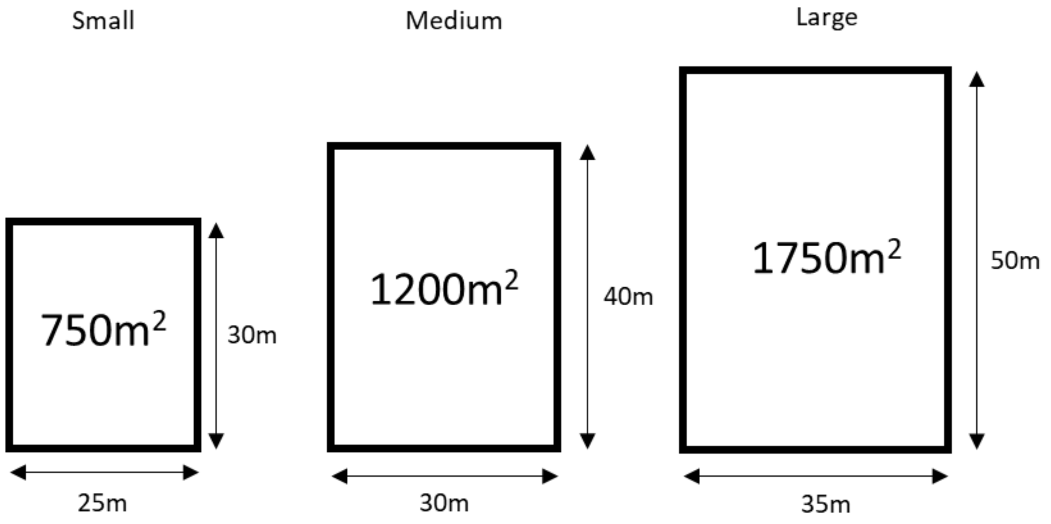
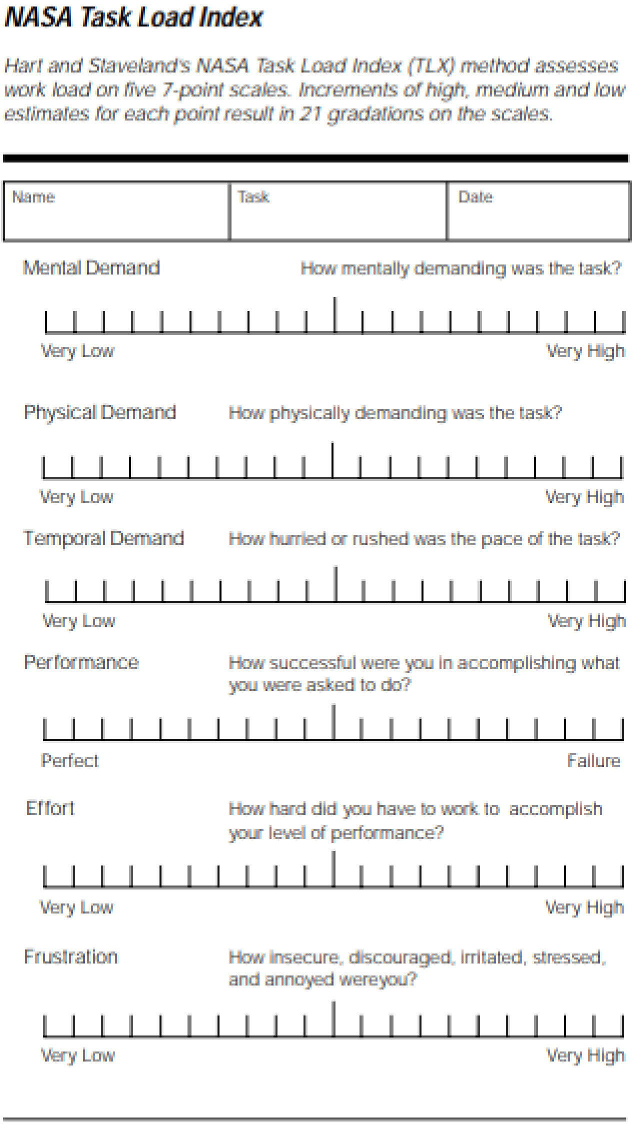


Figure 5. Pitch sizes to be used in the small-sided games

To assess changes in physical demands during the small-sided games participants will be equipped with global navigation satellite systems (GNSS), and heart rate monitors. The GNSS device collects data such as running speeds, and accelerations. Additionally, to assess the internal response to the training drill, participants will complete a session ratings of perceived exertion questionnaire immediately following each drill. These questionnaires are a single question, “How was your workout?”. Participants respond on a 1-10 scale (Table 1), with responses manually recorded. Additionally, to assess cognitive load, participants will complete a six question task load index (Figure 2)

Table 1. SRPE Scale [28]

0	Rest
1	Very, Very easy
2	Easy
3	Moderate
4	Somewhat Hard
5	Hard
6	.
7	Very Hard
8	.
9	.
10	Maximal



NASA Task Load Index

Hart and Staveland's NASA Task Load Index (TLX) method assesses work load on five 7-point scales. Increments of high, medium and low estimates for each point result in 21 gradations on the scales.

Name	Task	Date

Mental Demand — How mentally demanding was the task?
Very Low — Very High

Physical Demand — How physically demanding was the task?
Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?
Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?
Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?
Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?
Very Low — Very High

Figure 2. NASA TLX [256]

To assess technical and tactical demands of the training drills, sessions will be recorded, and manually analysed using a wide-lens camera. The camera will upload the footage to a cloud server, where the images will be processed, and then downloaded for analysis. The video capture tool (VEO) is standard use at the school and is frequently used to film Rugby and Football games and training sessions. An example of the data that will be extracted from the footage is number of involvements per minute per player. VEO data is automatically uploaded to VEO cloud servers. Given the use of video, participants anonymity may be compromised. However, no individual data will be reported in analysis, and following data analysis videos will be destroyed. VEO settings will be assigned to private, therefore access to videos will only be granted to those within the school administrative team with VEO access. Participants should be aware of the VEO and Catapult (GNSS Software) data processing agreement https://www.veo.co/en-au/data-processing-agreement, https://www.catapultsports.com/standard-terms. In particular, participants should be aware of the following clauses:

VEO data processing agreement subsection relevant to use of data

7.1.2 By uploading Content to the VEO Website, the Publisher hereby grants VEO a worldwide, perpetual, irrevocable, non-exclusive, royalty-free, fully paid-up, sub-licensable through multiple tiers and freely transferable right to copy, use, reproduce, distribute, publish, translate, modify, create derivative works of, publicly display, publicly perform, sell, transfer, license, edit, modify, transmit, stream, broadcast, making publicly available and otherwise exploit the Content on the Website as well as on and through third-party distributions channels selected by VEO, including without limitation for promoting, advertising, redistributing and making available on demand the Content and/or the VEO Website in any media formats, media channels or medium now or hereafter devised, in whole or in part, for any purposes. For the avoidance of doubt, the foregoing license includes, but is not limited to, the right to reproduce, distribute, display, perform, advertise, make derivative works from or otherwise exploit the Content in proximity with or in connection with any third-party content and the name, pseudonym, likeness, voice, handwriting and other characteristics of any individual, in each case where such items are in included in Content uploaded by the Publisher.

Catapult (GPS software) terms and conditions relevant to data usage

13 (b) You agree that Catapult may, and hereby grant Catapult the rights to:

i. access, use, adapt, modify, reproduce, reformat, transform, and process the Data during the Term to the extent necessary to provide the Equipment, Software and Services and to otherwise perform Catapult's obligations under this agreement;
ii. during or after the Term create Derivative Materials from the Data, only to extent that the Derivative Materials do not incorporate your Confidential Information in a form that could reasonably identify any individual; and
iii. during or after the Term use information about you, users of the Equipment and Software, or your use of the Equipment, Software and Services, for the purpose of improving the Equipment, Software and Services, detecting and addressing threats to the functionality, security, integrity and availability of the Software, detecting and addressing breaches of this agreement or any of Catapult's other policies and to help Catapult to resolve service requests.

How much time will the project take?

This project will take seven training sessions of approximately 45 minutes.

Are there any risks associated with participating in this project?

Any project that involves exercise will carry with it some form of risk, such as muscular strains and sprains. To mitigate these risks all participants will complete a warm-up prior to any testing, supervised by a qualified strength and conditioning coach. Additionally, participants are required to have had previous training experience.

What are the benefits of the research project?

Whilst there will be no direct benefits, such as financial compensation, to participate in this study, there will be indirect benefits. Throughout this study we will be able to carefully analyse training to enable greater planning of training drills. Long term this project will give greater knowledge as to how drill manipulation influences the demands on adolescent athletes, allowing coaches and directors of sports at St Joseph's Nudgee College to ensure they are delivering a world class program.

Can I withdraw from the study?

Participation in this study is completely voluntary. You are not under any obligation to participate. If you agree to participate, you can withdraw from the study at any time without adverse consequences. Following the data-collection period, you will no longer be able to withdraw your data as it will be de-identified and used for analysis.

Will anyone else know the results of the project?

The results of this study will be published within a peer-reviewed sport science journal. All published information will not be identifiable. Additionally, non-identifiable information from this study will be presented to the St Joseph's Nudgee College activities department.

Will I be able to find out the results of the project?

Once the project is published, you will be able to read the final manuscript.

Who do I contact if I have questions about the project?

Please feel free to contact Mr. Charles Dudley at charles.dudley@myacu.edu.au

What if I have a complaint or any concerns?

The study has been reviewed by the Human Research Ethics Committee at Australian Catholic University (review number 2022-2717). If you have any complaints or concerns about the conduct of the project, you may write to the Manager of the Human Research Ethics and Integrity Committee care of the Office of the Deputy Vice Chancellor (Research).

Manager, Ethics and Integrity
c/o Office of the Deputy Vice Chancellor (Research)
Australian Catholic University
North Sydney Campus
PO Box 968
NORTH SYDNEY, NSW 2059
Ph.: 02 9739 2519
Fax: 02 9739 2870
Email: resethics.manager@acu.edu.au

Any complaint or concern will be treated in confidence and fully investigated. You will be informed of the outcome.

I want to participate! How do I sign up?

Both student and parent consent forms can be signed electronically. Please contact Charles at charles.dudley@myacu.edu.au , or come to the activities office if you are interested in participating.

Yours sincerely,

Charles Dudley

Please retain a copy of this information letter