Monitoring Training Load and Responses to Load in Youth Soccer

Special Reference to Biological Maturation

by

Ludwig Ruf

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Abstract

Athlete monitoring is widely considered as an important part within the physical training process, which aims to maximise sports performance and health of an athlete. Within this training process the two constructs of training load and responses to load constitute the athlete monitoring framework. Given the lack of established gold standards, psycho-physiological responses are quantified by surrogate measurement instruments from multiple domains of the human body including but not limited to the cardiorespiratory, metabolic, neuromuscular, biochemical, endocrine, and musculoskeletal system. The selection of the most appropriate measurement instrument requires scientific evaluation of critical measurement properties such as reliability, validity, and responsiveness, while also considering several key aspects such as specificity to the sport, scalability and time efficiency when administered to large groups of athletes.

Despite considerable research in the area of athlete monitoring over the past decade, most research has been conducted in senior male professional team sport. Given the unique set of psychological and physiological characteristics and environmental circumstances of adolescent athletes it is unclear whether the previously established knowledge about the measurement properties of the most commonly used measurement instruments can be transferred to youth athletes. Therefore, the overall aims of this thesis were to advance the field of applied research in high-level soccer by firstly comparing a new device measuring skeletal age to the established method of percentage of predicted adult height as two potential practical, non-invasive methods to assess biological maturation status. Secondly, the reliability and responsiveness of commonly used measurement instruments that aim to assess acute psycho-physiological responses to load of youth soccer players were critically evaluated.

To establish a context and informed backdrop for the rest of the thesis, it was perceived as important to firstly investigate the validity of a non-invasive device which enables to enables practitioners to measure skeletal maturity within the applied setting. Results of the first study showed that the novel device to measure skeletal age based on an ultrasound-technique can be used to assess biological maturity status without the typically associated limitations of traditional standard radiographs. In addition, there was a maturity-related selection bias towards players advanced in biological maturation emerging in the U14 age group, which remained relatively constant throughout adolescence.

Subsequently, reliability and responsiveness as two important measurement properties were investigated for commonly used measurement instruments within youth soccer high-performance programs. Results of the second study showed that most of the included parameters possess poor short-term between-days reliability irrespective of the maturity status. Regarding the responsiveness, study three suggested that most investigated measurement instruments to assess acute psycho-physiological responses showed trivial to small changes to a short-period of accumulated training load during the in-season. During intensified periods of increased training load such as a short pre-season training camp as investigated during study four, the athlete-reported recovery and stress scales of the SRSS and heart rate responses during the sub-maximal run showed small to moderate changes in temporal relation to fluctuations in training load and might therefore be useful measurement instruments within the athlete monitoring process for adolescent soccer players. In contrast, parameters derived from the force-time data of a CMJ might provide little insight into acute neuromuscular responses to load.

Together the findings of the thesis allow practitioners to better understand the usefulness of commonly used measurement instruments. Results may also help practitioners in the selection process as to which measurement instruments are worthwhile implementing within their daily practice. In addition, findings of this thesis have important implications as they help guiding future research from a methodological and conceptual perspective to further advance the field of monitoring acute responses to load in youth soccer players. This ultimately may help practitioners in more accurately prescribing training load to elicit the desired adaptations and potentially mitigating injury risk in the long-term.

List of Publications Incorporated into this Thesis

The below list outlines the published and in press studies that are incorporated into this thesis. The studies listed below are presented in full in the following Chapters of this thesis.

Chapter 4

Construct validity of percentage of predicted adult height and BAUS skeletal age to assess biological maturity in academy soccer

Ruf, L., Cumming, S., Härtel, S., Hecksteden, A., Drust, B., & Tim Meyer

Annals of Human Biology, 2021, 48(2), 101-109

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Chapter 5

Poor reliability of measurement instruments to assess acute responses to load in soccer players irrespective of biological maturity status

Ruf, L., Drust, B., Ehmann, P., Skorski, S., Hecksteden, A., & Meyer, T.

Pediatric Exercise Science, 2022, 34(3), 125-134

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Chapter 6

Are measurement instruments responsive to assess acute responses to load in high-level youth soccer players?

Ruf, L., Drust, B., Ehmann, P., Skorski, S., & Meyer, T.

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Chapter 7

Psycho-physiological responses to a pre-season training camp in high-level youth soccer players

Ruf, L., Altmann, S., Härtel, S., Skorski, S., Drust, B., & Meyer, T.

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List of Abbreviations

ARSS	Acute Recovery and Stress Scale
AU	Arbitrary unit
BA	Biological age
CA	Chronological age
CI	Confidence interval
CK	Creatine kinase
CMD	Countermovement depth
CMJ	Countermovement jump
ConI	Concentric impulse
ConV	Concentric velocity
CV	Coefficients of variation
DurCon	Duration of concentric phase
DurEcc	Duration of eccentric phase
EccI	Eccentric impulse
EccV	Eccentric velocity
ES	Effect size
F@0V	Force at zero velocity
G1	Genitalia stage 1
G3	Genitalia stage 3
G5	Genitalia stage 5
GLONASS	Russian Globalnaya Navigazionnaya Sputnikovaya Sistema
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HI	Heat index
HR	Heart rate
HRR	Heart rate recovery
HRR60	Heart rate recovery 60s
HRV	Heart rate variability

ICC	Intra-class correlation coefficient
ISAK	International Society for the Advancement of Kinanthropometry
JH	Jump height
MEMS	Micro electrical mechanical systems
MIC	Minimal important change
MTDS	Multi-Component Training Distress Scale
N	Newton
PH1	Pubic hair stage 1
PH3	Pubic hair stage 3
PH5	Pubic hair stage 5
PHV	Peak height velocity
PPAH	Percentage of the predicted adult height
RESTQ	Recovery Stress Questionnaire for Athletes
RFD	Eccentric rate of force development
RPE	Rating of perceived exertion
RSI	Reactive strength index
RSImod	Reactive strength index modified
SA	Skeletal age
SD	Standard deviation
SDC	Smallest detectable change
SDC90	Smallest detectable change at 90% confidence level
SEM	Standard error of measurement
SHT	Submaximal hopping test
SMD	Standardized mean differences
SRSS	Short Recovery and Stress Scale
TE	Typical error of measurement
TEM	Technical errors of measurement
TRIMP	Training impulse
TW	Tanner-Whitehouse
UK	United Kingdom

Navigation of Thesis

Youth academies play a pivotal role in developing youth soccer players by enabling them a safe and healthy environment to progress towards senior professional soccer. to avoid maladaptive training outcomes, measurement instruments are typically used to monitor psycho-physiological responses to load. However, many of the measurement instruments commonly used in high-level youth soccer have yet to be supported by science. Typically, these measurement instruments are implemented first in practice while their usefulness is critically scrutinized by the scientific community later. Therefore, this thesis aims to close this gap by contributing important information to the scientific body of research whether commonly implemented measurement instruments can be confidently used to monitor acute psycho-physiological responses to load in high-level youth soccer players.

Chapter 1 provides a general introduction to the thesis, including a description of the overall purpose and aims of implementing a holistic athlete monitoring system to assess and monitor biological maturity, training load and responses to load in a high-level youth soccer environment.

Chapter 2 provides background information regarding the monitoring of training load and psycho-physiological responses to load in high-level youth soccer players. The initial part of the literature review describes the physical and physiological demands of training and matches. It follows a brief overview over methods to determine biological maturation. Subsequently, a critical overview will be provided regarding measurement instruments to monitor training load as well as acute and chronic psycho-physiological responses considering the individual and contextual factors influencing the psycho-physiological responses to load. Finally, measurement properties of measurement instruments to monitor psycho-physiological responses to load will be discussed.

Chapter 3 describes the research aims and objectives of the experimental studies within this thesis.

Chapter 4 examines the convergent validity of the BAUS^{TM} system to estimate the biological maturity status by comparing skeletal ages derived from the BAUS^{TM} system with percentage of predicted adult height derived from the Khamis-Roche method and by examining the magnitude of maturity-related selection biases across age groups.

Chapter 5 explores the short-term between-day reliability of measurement instruments to monitor the acute psycho-physiological response to load in youth soccer players in relation to biological maturity status.

Chapter 6 examines the short-term responsiveness of measurement instruments to assess acute psycho-physiological responses to load in high-level youth soccer players.

Chapter 7 describes the time-course of psycho-physiological responses to a short pre-season training camp in high-level youth soccer players.

Chapter 8 provides a general discussion of the thesis, including a summary of findings, limitations associated with this thesis, practical applications to implementing an athlete management system in a high-level youth soccer environment, and an outline for future research.

Chapter 9 and Chapter 10 contain all references used throughout this thesis and appendices, respectively.

Chapter 1: General Introduction

Soccer (association football) is considered to be one of the most popular sports played among adult men and women as well as male and female children and adolescents. Soccer continues to growth in terms of both participation and commercial revenue, as indicated by the increasing transfer fees and salaries for both players and coaches at the professional level. Professional soccer is the highest level with elite female and male adult players representing teams at the highest national and international level. Youth academies play an important role in this context their most important missions and visions are to develop and nurture prospective players on the pathway towards senior professional soccer, to support personal development and to strive for financial profit (Relvas et al., 2010).

Sports performance in soccer is determined by the interaction of a plethora of various aspects including but not limited to technical, tactical, psychological and physical key performance characteristics (Sarmento, Anguera, et al., 2018). The concept of key performance indicators describes the idea that stakeholders, coaches, and practitioners use quantifiable measures to evaluate progress against a target. Even though technical, tactical and psychological key performance indicators are of grave importance, physical qualities are also considered as important determinants of soccer performance (Kite et al., 2022; S. J. Roberts et al., 2019). From a physical performance perspective, soccer is an intermittent sport requiring a mixture of physiological qualities including the aerobic and anaerobic energy system as well as neuromuscular qualities including speed, agility, mechanical power, and strength. Over recent years physical locomotor match performance, particular high-intensity running and sprint distances, has increased substantially in elite senior soccer players (Barnes et al., 2014). This has indirect consequences on the strategies and training programs put in place for youth soccer players striving towards the senior professional level. Coaches and practitioners working within youth soccer academies need to adopt a forward thinking approach by constantly maximising the development of physical qualities in order to adequately prepare current youth players for the increased physical demands at the highest professional level. It follows that key stakeholders need to identify youth soccer players who possess well developed key physical qualities while practitioners and coaches within high-performance programs have to further develop these physical qualities so that youth soccer players can withstand the continuously increasing physical demands across age groups on their path towards senior professional soccer.

Talent identification and development processes of youth academies is a large field within youth academies of professional soccer clubs. Talent identification is defined as recognising players who have the potential to progress into high-performance development programs of professional youth academies or national associations (Williams et al., 2020). Talent development refers to the systematic combination of coaching, support, training and match play to progress players (Williams et al., 2020). Over the past two decades talent identification and development processes of youth soccer players have become professionalised, whereby youth academies, national governing bodies, coaches and families invest a significant amount of resources from a financial, personal and time perspective. Early identification and recruitment into a high-performance program is a cornerstone in the long-term development of physical and soccer-specific performance (Unnithan et al., 2012). Key elements identified by the scientific literature with regards to talent identification and development processes is the environment surrounding the player including their family, coaches as well as life experiences, sports experiences, and the actual training program implemented by the coaches of the youth academy (Ford et al., 2020). A multidisciplinary approach is therefore required to identifying and developing youth players by measuring a number of key performance indicators from several domains of sports performance. One aspect that has considered to be an important part of the training process to maximise sport performance and health is the implementation of an athlete monitoring system.

Recent advancements in the area of sports technology across the past decade allowed coaches, practitioners, and researcher alike to implement an increasing number of wearables to scientifically explore several aspects of sports performance. This eventually led to the systematic and widespread proliferation of strategies to investigate and monitor training load (i.e., a construct reflecting the amount of physical training done and experienced by the athlete), responses to load (i.e., effects cased and occurring after a single or a series of training sessions) and sport-specific performance outcomes as part of athlete monitoring systems to maximise sports performance and health (Jeffries et al., 2021). While fairly rudimentary at the time, the first field-based monitoring systems included the collection of heart rate data during the late 1990's (Drust, 2019). This data provided valuable information and fundamental proof of concept for today's commonly implemented strategies to quantify and monitor the internal load as part of the athlete monitoring system. Around the same time, the session rating of perceived exertion (sRPE) method was adapted by Foster et al. (2001, 2021) based on the seminal work of Gunnar Borg who developed the rating of perceived exertion (RPE) method (Borg, 1998). The sRPE represents the post-hoc appraisal of the RPE for an entire training session or match. When multiplied by the duration of the training session or match, sRPE training load can be quantified serving as a measurement instrument of internal training load (McLaren et al., 2018). During the late 1990's, the introduction of multi-camera systems in stadiums particularly in the UK has also become more and more established allowing the quantification of external load and thus physical performance of the match itself. While limited to matches this led to a new wealth of information regarding the physical demands to support the development of training strategies aiming to maximise sports performance for both researchers and practitioners. The adoption of Global Navigation Satellite System (GNSS) technology such as the US Global Positioning System (GPS) and the Russian Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS) within high-performance sports during the early 2000's was the next revolutionary step in quantifying external load through rudimentary locomotive parameters during training sessions (Aughey, 2011). The subsequent development in micro-technology over the past decade led to the incorporation of other micro inertial sensors such as accelerometers, magnetometers and gyroscopes, collectively termed as micro electrical mechanical systems (MEMS) (Malone et al., 2016). This technology provided researcher and practitioner with an increasing number of sophisticated parameters and thus the possibility to better understand the physical demands of soccer training. Today, GNSS technology in combination with multi-camera systems has become a key component within athlete monitoring systems in high-performance sports to quantify the external load of any given training session or match and help with programming the optimal training load to elicit the desired psycho-physiological responses (Impellizzeri et al., 2019; Malone et al., 2020). Historically, this response to load has been acquired by coaches in a qualitative manner by asking the athlete for example how they cope with the training or by interpreting their physiognomy and body language. Although the qualitative coach-athlete relationship will always have value there exists now a wide array of measurement instruments quantifying subjective and objective responses to load from the cardiorespiratory, metabolic, neuromuscular, and musculoskeletal system (Cardinale & Varley, 2017). It is this psycho-physiological response to a given stimulus that ultimately drives training adaptation highlighting the importance on both measuring and managing the training load and associated responses. This is considered as an essential aspect of athlete monitoring systems nowadays which allows coaches and practitioners to evaluate the effectiveness of a training program, manage subsequent training load and program adequate recovery.

Adolescence is a unique stage of psycho-social, cognitive, sexual, and physical development and typically spans from 10 to 19 years of age in males. This is accompanied with non-linear psychological, neuromuscular, and physiological changes throughout adolescence. Adolescents of the same chronological age (CA) vary substantially in both growth and biological maturation characteristics. In this context growth refers to the increase in the size of the body as a whole and of its parts (Malina, 2017). Although it is difficult to separate growth and biological maturation as they occur concurrently, they do not constitute the same constructs. As such, biological maturation refers to the progress towards the biologically mature state of each tissue, organ and system of the body (Malina, 2017). Biological maturation is assessed in terms of status, i.e., level of maturation at the time of observation), timing (chronological age at which specific maturational events occur), and tempo (rate at which maturation progresses) (Malina et al., 2015). For coaches and practitioners working with youth soccer players, particularly around the growth spurt, i.e., U13 through to U15 age groups, it is common to observe very large differences between players within the same competitive age group with regards to for example standing height and skeletal age, an indicator of biological maturity status. At the extrema differences of up to 30 cm in standing height and five years skeletal age have been reported in high-level soccer players of similar CA (Figueiredo et al., 2009b, 2010; Johnson et al., 2017; Malina, Eisenmann, et al., 2004).

Many direct and indirect practical implications arise for various key stakeholders within the high-level youth academy setting such as coaches, scouts, physiotherapists, sport scientists, and strength and conditioning coaches as a consequence of such inter-individual differences in terms of growth and biological maturation. These include but are not limited to talent identification, talent development and athlete monitoring processes. Touching on the last aspect, although there has been an exponential increase in scientific endeavour within the field of applied athlete monitoring, research has focussed largely on senior professional team sport populations. Despite the paucity of research within the youth population, practitioners adopted largely similar strategies used by their senior counterparts employing the same measurement instruments to assess and monitor training load and psycho-physiological responses to load. Consequently, more research is warranted investigating the appropriateness of athlete monitoring systems within high-level youth soccer players by examining the usefulness of the measurement properties of measurement instruments assessing psycho-physiological responses to load. This information helps practitioners in selecting measurement instruments based on theoretical, technical, contextual, and also scientific considerations to ultimately maximise the development of youth soccer players on their pathway towards senior professional soccer.

Chapter 2: Literature Review

2.1 Physical training and match demands of youth soccer

Training and match demands of senior professional soccer players has been studied extensively across the past two decades (Anderson, Orme, Michele, et al., 2016; Kelly et al., 2020; Martín-García et al., 2018; Stevens et al., 2017). Comparatively few studies examined weekly training and match loads in youth soccer players across adolescence (Palucci Vieira et al., 2019). Information about the physical match demands may assist practitioner in planning and implementing training strategies to physically challenge and prepare players for the increasing demands of older age groups and particularly the senior professional level (Barnes et al., 2014).

2.1.1 Physical demands of matches in youth soccer

Total distance increased by approximately 35% from U9 to U12, which is mainly due to an increase in moderate and high-speed running (Goto et al., 2015a, 2015b; Harley et al., 2010; Saward et al., 2015). U9 and U10 players cover between 4000-4500 m per match (~60 $m.min^{-1}$) with only a fraction of it being at high-speed (~4%) (Goto et al., 2015b). Larger total distances (~4500-5700 m; ~65 $m.min^{-1}$) were also reported for both U9 and U10 age groups, likely as a result of different match configurations used (i.e., number of players, duration, pitch size) (Saward et al., 2015).

In the U11 and U12 age groups a slight increase in total distance covered (5500-6000-m; ~80 $m.min^{-1}$) has been reported on both a group-based and positional level (Harley et al., 2010) even after adjusting for the increased match duration (Saward et al., 2015). On a positional level, only small differences between positions were evident (Saward et al., 2015). However, caution is needed when interpreting the magnitude of these differences as the game-to-game variation was large for all age groups and metrics analysed.

Total distance covered ranged from ~6000-7500 m (~80-110 $m.min^{-1}$) in the U13 to ~6000-8000 m (~75-115 $m.min^{-1}$) in the U14 and ~6200-8100 m (~80-100 $m.min^{-1}$) in the U15 age group with considerable variability between studies (Buchheit, Mendez-Villanueva, Simpson, et al., 2010b; Castagna et al., 2009, 2010; Goto et al., 2015a; Harley et al., 2010; Mendez-Villanueva et al., 2013; Parr et al., 2021; Saward et al., 2015; Waldron & Murphy, 2013). Relative distance was however somewhat similar across age groups (Atan et al., 2016). This might be due to different durations of match play (e.g. U15: 2x30 min (Castagna et al., 2010) vs 2x40 min (Buchheit, Mendez-Villanueva, Simpson, et al., 2010b)), pitch sizes, playing standards or styles (Buchheit, Mendez-Villanueva, Simpson, et al., 2010b). There is a large variety in the methods used to determine thresholds for speed zones (e.g. arbitrary percentages from 10-20-m flying speed (Saward et al., 2015), arbitrary percentages from locomotor entities (Mendez-Villanueva et al., 2013), equal categories from 0 $m.s^{-1}$ to two standard deviations below 5-10m flying speed (Goto et al., 2015a)), which consequently does not allow direct comparison between studies. However when examining the changes in distance covered in various speed zones within studies small increases from U13 to U15 were evident only when not adjusting for total playing time (Buchheit, Mendez-Villanueva, Simpson, et al., 2010b; Mendez-Villanueva et al., 2013; Saward et al., 2015). This indicates that increases in match running performances are predominately the result of the increased match durations and to a lesser extent due to increases in physical qualities (Buchheit, Mendez-Villanueva, Simpson, et al., 2010b). Interestingly, in these age groups and similar to their adult counterparts (Di Salvo et al., 2013), match running performance appears to be affected by playing position, with central midfielders covering the most total distance while greater high-speed and sprint distances were reported for wide midfielders and striker (Buchheit, Mendez-Villanueva, Simpson, et al., 2010b; Duthie et al., 2018; Mendez-Villanueva et al., 2013; Saward et al., 2015).

Furthermore, during international youth matches, a linear increase in repeated sprint sequences (≥2 consecutive, ≥1s sprints interspersed by <60s of recovery) was observed from the U13 through to the U18 age group when using an absolute threshold (Buchheit, Mendez-Villanueva, Simpson, et al., 2010a). Peak speed, acceleration and metabolic power demands for different durations (i.e., 1-10 min) were examined by applying a power-law modelling technique to determine the peak demands experienced by high-level youth soccer players (Duthie et al., 2018). Although there were large similarities between age groups (U15-U17), substantial differences were observed between positions for peak running speeds and metabolic power reflecting the differing demands across positions. From a practical perspective, these data provide information to how optimally prescribe and quantify the locomotor demands of sport-specific training drills with respect to peak match demands (Delaney et al., 2018; Whitehead et al., 2018). From a conceptual perspective however, concerns have been raised related to the univariate analysis and interpretation of match running performance parameters, the lack of consistent temporal occurrence of peak demands across different match running performance parameters, and the failure to adequately prepare players for the true peak demands, when preparing players to meet a previous individual or positional average peak demand (Novak et al., 2021).

Similar to the increase in total distance across the younger age groups, a small increase (approximately +20%) in total distance covered during competitive matches has been observed from the U16 to U18 age group, likely due to increases in match duration. Reported total distance covered ranged from ~6500-8500-m (~80-105 $m.min^{-1}$) at the U16 to ~6600-11000-m (~105-120 $m.min^{-1}$) at the U17 and ~6600-8900-m (~90 $m.min^{-1}$) at the U18 level (Buchheit, Mendez-Villanueva, Simpson, et al., 2010b; Goto et al., 2015a; Harley et al., 2010; Mendez-Villanueva et al., 2013; Rebelo et al., 2014; Saward et al., 2015; Varley et al., 2017). Similarly, when using fixed speed thresholds, older age groups covered more distance at high speeds compared to their younger counterparts, even after adjusting for total time played (Buchheit, Mendez-Villanueva, Simpson, et al., 2010b; Saward et al., 2015). However, no meaningful differences were reported for distances covered at higher speeds when adopting an individualised approach to determine speed thresholds (Mendez-Villanueva et al., 2013).

Limited data is available regarding the internal load players are exposed to during competitive match play. Three studies continuously measuring heart rate during competitive matches observed large similarities across age groups (i.e., U14-U18) and playing positions (Castagna et al., 2010; Mendez-Villanueva et al., 2013; Rebelo et al., 2014). Specifically, players spent approximately 65-75% of their playing time above 80% of their maximal heart rate which is similar to what has been reported for elite adult soccer players (Alexandre et al., 2012). Interestingly, heart rate responses during standardised simulated soccer activities (i.e., Y-SAFT^{60}) was not substantially moderated by biological maturation status from players o the U13 to U16 age group (Salter, Croix, & Hughes, 2021).

Further, evidence suggests that maturation status might have an impact on match running performance (Buchheit & Mendez-Villanueva, 2014; Lovell et al., 2019; Parr et al., 2021). Early maturing players within the U15 age group demonstrated greater peak running speeds and covered slightly to moderately more distance at higher speeds (>16.0 km.h^{-1}) despite no difference in total distance between early and on-time maturing players (Buchheit & Mendez-Villanueva, 2014). In contrast and somewhat surprising, greater distances at high-speed (>13.0 km.h^{-1}) and very-high speed (>16.0 km.h^{-1}) have been reported in later maturing players among a U15 national federation cohort, although the magnitude of the differences might be considered as trivial (Lovell et al., 2019). Finally, in U14 youth soccer players from an English professional soccer academy, advanced biological maturation was only associated with increased high-speed running distance (>19.8 km.h^{-1}), while no association was evident for the U15/16 cohort or any physical match performance parameter (Parr et al., 2021). Collectively, these data suggest that biological maturation has an impact on match running performance, yet this impact is of small magnitude and pertains more the younger age groups.

2.1.2 Physical demands of training in youth soccer

Typically, during the in-season, U10 to U16 age groups are engaged in 3-4 training sessions per week, while U17 to U19 age groups complete 4-5 training sessions per week (Abade et al., 2014; Brownlee et al., 2018; Coutinho et al., 2015; Gil-Rey et al., 2015; Hannon, Coleman, et al., 2021; Wrigley et al., 2012). Weekly training duration is comparable amongst the younger age groups (i.e., U12 to U14) with ~350-400 min per week and increased in the older age groups (i.e., U15 to U18) with ~400-450 min per week (Hannon, Coleman, et al., 2021), although higher (~550-600 min per week)

(Wrigley et al., 2012) and lower (~200-250 min per week) (Brownlee et al., 2018) training durations have been reported for the older age groups.

Similar to weekly training duration, weekly total distance follows a similar pattern whereby younger age groups (i.e., U12 to U14) cover less (~20-22 km per week) than their older (i.e., U15 to U18) counterparts (~25-26 km per week), while relative total distance was similar across all age groups (Hannon, Coleman, et al., 2021; Hannon, Parker, et al., 2021). Greater weekly total distances reflect therefore an increased number or longer training sessions as opposed to increased players' physical abilities. Interestingly, weekly total distances from the older age groups (i.e., U15 to U18) are comparable to weekly distances during a one game per week micro-cycle in senior English Premier League (Anderson, Orme, Di Michele, et al., 2016; Kelly et al., 2020), but somewhat lower than Dutch Eredivisie players (~30-32 km per week) (Stevens et al., 2017).

Weekly high-speed (19.8-25.2 $km.h^{-1}$) and sprint distance (>25.2 $km.h^{-1}$) increased linearly from the U12 (~240 m high-speed and ~10 m sprint distance) to U18 (~1000 m high-speed and ~100 m sprint distance) age group with considerable inter-individual variability, likely reflecting the considerable variation in biological maturation and greater position specific profiles in these age groups (Hannon, Coleman, et al., 2021). Interestingly again, similar weekly high-speed running distances have been reported for senior English Premier League player during a one game per week micro-cycle (~900 m per week), however weekly sprint distance was slightly greater in the senior soccer population (Anderson, Orme, Di Michele, et al., 2016). The progressive increase in high-speed and sprint distance throughout adolescence coincides with the continues development in maximal sprinting speed as a result of systematic sprint training and as a result of the natural improvements due to growth and biological maturation (Meyers et al., 2017). Considering the substantial biomechanical load associated with high-speed running and sprinting (Schache et al., 2011), this opens up the potential need to closely monitor training load (i.e., high-speed and sprint distance), the associated internal biomechanical load (i.e., muscle-tendon forces (Vanrenterghem et al., 2017)), and subsequent psycho-physiological responses to load (i.e., kinematics of a countermovement jump (Jeffries et al., 2021)) in relation to the biological maturation of the youth soccer player. Despite representing important indicators of biomechanical load due to their potential relevance for injury risk (Harper et al., 2019; McBurnie et al., 2022), weekly data across the entire adolescence regarding accelerations, deceleration and change of direction (e.g., 25 accelerations over 2 $m.s^{-2}$, for a total distance of 300 m) or other data derived from micro inertial sensors (e.g., PlayerLoad™ of 450 AU) is scarce.

Similar to senior professional soccer players (Kelly et al., 2020; Malone, Di Michele, et al., 2015a), players experience the highest training load during a one game per week micro-cycle on match day (Hannon, Coleman, et al., 2021; Maughan et al., 2021). This was evident for several training load indicators such as total, high-speed running and sprint distance as well as number of accelerations and decelerations. There are however differences in the loading distributions across age groups throughout the weekly micro-cycle likely reflecting the shift towards preparation for competition in the older age groups and the different psycho-physiological responses to load in younger, less mature to older, more mature adolescents (Murray, 2017). Specifically, there was very little variation in total, high-speed, and sprint distance for the U12 and U14 age groups (Hannon, Coleman, et al., 2021). In contrast, a consistent pattern was evident for the U15 through to the U18, with match-day minus 4 representing the day of the highest total, high-speed, and sprint distance. Significant reductions were then observed for all parameters on match-day minus 1 in preparation for the match. Similar loading distributions throughout the weekly micro-cycle have been observed in senior professional soccer players (Anderson, Orme, Di Michele, et al., 2016; Houtmeyers et al., 2021; Kelly et al., 2020). Periodisation strategies of the weekly micro-cycle emerging from the U15 age group coincide with players typically transitioning into the pre-pubertal status into the growth spurt (Malina et al., 2015; McBurnie et al., 2021). During this period players experience rapid changes in body size (i.e., standing height, body mass, fat free mass etc.) which are accompanied with substantial changes in physiological, neuromuscular and psychological profiles (Beunen & Malina, 1988; Remschmidt, 1994). This period has also been associated with increased risk of sustaining growth related injuries (Johnson et al., 2020; Monasterio et al., 2021; Rejeb et al., 2019; Wik et al., 2020). The adaptation of muscles, tendons, and apophyses typically occurs after the rapid growth of bones exposing the muscle-tendon junction to increased stress (Caine et al., 2014). Other factors such as reduced bone mineralisation, decreased physeal strength, and impaired motor coordination contribute to the susceptibility of the adolescent athlete during the growth spurt (Caine et al., 2008). Growth-related injuries predominately are caused by the failure of the musculoskeletal structures to the high exposure to repetitive and excessive biomechanical loads (DiFiori et al., 2014). As training load typically increases as players transition towards the older age groups (i.e., from U13 to U16), coupled with the increased vulnerability of bodily tissues, players are exposed to increased injury risk. Therefore, it is paramount to closely monitor growth, biological maturation, training load and associated responses to load this sensitive period to enable youth soccer players a safe and healthy environment to progress through adolescence injury free.

2.2 Biological maturation in youth soccer

Biological maturation refers to the progress towards the biologically mature state (Malina, 2017). This progress varies across all biological systems of the body, such as the skeletal, sexual, somatic, neuroendocrine and dental system (Malina et al., 2019). Biological maturation can be assessed in three different ways; first, in terms of status, i.e., the state of maturation at the CA of observation, second, in terms of timing, i.e., the CA at which specific maturational events occur, and third, in terms of tempo, i.e., the rate at which maturation progresses (Malina et al., 2015). While difficult to separate from biological maturation, growth refers to the increase in the size of the body as a whole, i.e., changes in biological systems associated with body size such as standing height, body mass and circumferences (Malina et al., 2019). A third process that occurs from childhood to adulthood, but which will not be explored in depth in this thesis, is termed development which refers to the acquisition and refinement of various forms of behaviour including cognitive, social, emotional and moral elements specific to the culture an individual grows up (Malina et al., 2019). Although all three processes interact and occur at the same time with interactions being particularly prominent during adolescence the following sections solely focuses on biological maturation by providing an overview over various methods and protocols to determine biological maturation followed by highlighting the maturity-related selection bias during adolescence and finishing off with describing the resulting implications.

2.2.1 Methods and protocols to determine biological maturation

As biological maturation varies according to the biological system of interest, several indicators exist to determine the status and timing. The most commonly indicators include the assessment of skeletal, sexual, and somatic maturation.

2.2.1.1 Skeletal maturation

Traditionally, the bones of the left hand and wrist provide the basis for assessing skeletal maturation and expressed as skeletal age. In paediatrics and other clinical fields, skeletal age is determined via visual assessment of a standard radiograph of the hand-wrist skeleton (Cameron, 2004). Other body parts such as knee and ankle have also been used to determine skeletal age (Malina, Bouchard, et al., 2004). Each bone goes through irreversible changes of the metamorphosis of the cartilaginous and membranous tissue until full ossification is achieved. Each bone goes through relatively uniform changes from initial ossification to adult morphology which can be evaluated on the standard radiograph and form the basis for the various methods to assessing skeletal age of an individual. There are three methods to determine skeletal age based on the hand-wrist skeleton, Greulich-Pyle (Greulich & Pyle, 1959), Tanner-Whitehouse (TW1, TW2, and TW) (Tanner et al., 1975, 1983, 2001), and Fels (Roche et al., 1988). All three methods are similar in principle, yet reference populations and specific criteria to determine skeletal age differ. (Malina, 2011). As such, skeletal ages derived with each method are, although correlated, not equivalent. The skeletal age of an individual represents the state of skeletal maturation attained at the CA of observation in relation to the reference method. Full skeletal maturation is indicated as skeletally mature, an skeletal age is not assigned, irrespective of the method, although criteria vary as to when an individual is skeletally mature (Malina, 2011). To contextualise the skeletal age of an individual it is expressed relative to the CA. The difference between skeletal and chronological age and ratio of skeletal to chronological age are most commonly used. The difference between skeletal and chronological age is also often used to classify individuals as late (i.e., skeletal age younger than CA by >1.0 year), on-time (i.e., skeletal age within ±1.0 year of CA), and early (i.e., skeletal age older than CA by >1.0 year) (Malina, Bouchard, et al., 2004). The classification band of ±1.0 year, although somewhat arbitrarily, approximates standard deviations of skeletal ages within single-year male CA age groups during adolescence in the general population for the three different methods (Malina et al., 2012, 2018). However, care should be taken when dichotomising continuous variables into categories due to substantial loss in information, underestimation of variation in outcome between categories, and concealment of non-linear pattern between the variable and outcome (Altman & Royston, 2006).

Skeletal age can be determined from infancy through the entire childhood and adolescence, while other indicators of biological maturation are limited to specific periods of adolescence such as puberty. In addition, all three methods to determine skeletal age are valid and have high inter- and intra-rater reliability (Faustino-da-Silva et al., 2020; King et al., 1994; Moradi et al., 2012; Roche & Davila, 1976; Tanner et al., 1994; Wenzel & Melsen, 1982). Limitations of skeletal age determination include the lack of qualified personnel to take radiographs and interpret them according to the respective method, particularly in the applied youth high-performance setting, logistical constraints for individuals associated with the assessment, expenses associated with the radiographs, and exposure to minimal radiation (Malina et al., 2015). However, exposure to radiation represents a minimal risk, as it is less than natural background radiation and equivalent to three hours of daily television viewing (Radiological Society of North America, 2019).

Given these limitations, other protocols for the determination of skeletal maturity of the hand-wrist skeleton have been developed. These include deriving skeletal ages using automated methods to determine skeletal ages based on standard radiographs such as the BoneXpert (validated against Greulich-Pyle and Tanner-Whitehouse TW2) (Thodberg et al., 2009, 2012) and the application of ultrasound-based (Rachmiel et al., 2017) or magnetic resonance imaging protocols (Urschler et al., 2016).

2.2.1.2 Sexual maturation

Secondary sex characteristics provide the basis for assessing sexual maturation during puberty reflecting the pubertal status at the time of observation (Malina et al., 2015). In males, these characteristics include most often pubic hair, genitalia (penis scrotum, testes), and less often testicular volume, voice change and facial hair. Collectively, these characteristics reflect the maturation of several hormonal axes (i.e., hypothalamic-pituitary-end organ axes) of the neuroendocrine system (Beunen et al., 2006a). Most commonly, the five stages of pubic hair (PH1 through PH5) and genitalia (G1 through G5) as described by Tanner (1962) based on the work of Reynolds and Wines (1951) as well as Nicolson and Hanley (1953) are used to determine the pubertal status of an individual. Importantly, stages are discrete despite the continuous process of sexual maturation and not equivalent for pubic hair and genitalia (i.e., PH3 ≠ G3) (Malina, 2017). In addition, despite high correlation, there is considerable variability within a CA group and with regards to other indicators of biological maturation such as skeletal age (Figueiredo et al., 2009b, 2010). Traditionally, the assessment of sexual maturation has been obtained through visual observation of a physician in the clinical setting (Cameron, 2012). Inter- and intra-rater reliability among experienced examiner is generally good (Hergenroeder et al., 1999; Matsudo & Matsudo, 1994). As the assessment of secondary sex characteristics is invasive in nature, parents might see this as invasion of the child's or adolescent's privacy and refuse the assessment, particularly in the non-clinical setting such as high-performance sports. Protocols to self-assess the pubertal status have therefore been developed. The child or adolescent is asked to rate their stage of sexual maturation in relation to standardised photographs or schematic drawings of the respective stage (Malina, Bouchard, et al., 2004). Concerns have however been raised regarding the accuracy of self-assessment by the child or adolescent (Rasmussen et al., 2015; Rollof & Elfving, 2012; Schlossberger et al., 1992), although higher accuracy was reported in high-level adolescent athletes (Leone & Comtois, 2007). Other limitations include the limited the dissection of the continuous maturational process into discrete stages resulting in the loss of information regarding the pubertal timing (i.e., entry into a stage) and tempo (i.e., duration of a stage). Indicators of sexual maturation are limited to the pubertal phase of biological maturation and have thus limited applicability during childhood and late adolescence.

Given these limitations, the assessment of sexual maturation through secondary sex characteristic is barely implemented within high-performance development programs. Instead, practitioners rely on non-invasive indicators derived from anthropometric indicators to estimate somatic maturation.

2.2.1.3 Somatic maturation

Anthropometric indicators are no valid indicators of biological maturation, as body size at the mature state by itself is not the same for all individuals (Beunen et al., 2006a). Currently there are two indicators, percentage of predicted adult height as indicator of biological maturation status and predicted maturation offset as indicator of biological maturation timing (Malina et al., 2015).

Percentage of predicted adult height as an indicator of somatic maturation was initially proposed by Roche et al. (1983). The current standing height is divided by the predicted adult height to derive the percentage of predicted adult height. In two adolescents of similar CA, the one closer to the final adult height is more advanced in somatic maturity, irrespective of the current and predicted standing height. For instance, two 14-year-old boys have the same standing height of 165 cm, one of the boys is at the time of observation at 92% of his predicted adult height, while the other is at 88% of his predicted adult height. The former is therefore more mature than the latter. Percentage of predicted adult height is an indicator of the status of somatic maturation at a given CA. Traditionally, protocols to predict adult height required the skeletal age of an individual (Bayley & Pinneau, 1952; Roche et al., 1975; Tanner et al., 1983, 2001) which of course limits their applicability. To overcome this limitation, Khamis and Roche (1994) developed sex-specific equations to predict adult height for youth 4.0 to 17.5 years of age and requires the CA, current standing height, body mass, and the mid-parental standing height. Mean error at the 90th percentile between actual and predicted adult height was

5.3±1.4 cm (Khamis & Roche, 1994). Other protocols for estimating adult height based on anthropometric indicators in boys include the Beunen-Malina method which requires CA, standing height, sitting height, and the subscapular and triceps skinfold thickness (Beunen et al., 1997). Associated standard errors with this method are 3.0 to 4.2 cm. Limitation of these protocols include the lack of consideration of ethnic variations in the gender-specific equations, which can lead to inaccuracies in the estimation of adult height in non-Caucasian athletes. To classify adolescents as early, on-time and late, a z-score can be calculated by comparing the percentage of predicted adult height of an individual with the mean and standard deviation for a given CA of a reference sample. Often the reference data from the Berkeley Growth Study (Bayer & Bailey, 1959) are used to compute the z-score. Due to the lack of an uniform classification threshold value (Hill et al., 2019) and the disadvantages of dichotomising continuous variables, the z-score can be interpreted as follows: negative values indicate a late-developed, positive values an early-developed somatic maturity status. Information about the percentage of predicted adult height for an individual provides valuable insight as to whether the individual is approximately in the interval prior to the take-off of the growth spurt (<85.0% of predicted adult height), in the interval between take-off and peak height velocity (≥85.0% to <90.0% of predicted adult height), in the interval of peak height velocity (≥90.0% to <93.0% of predicted adult height) or in the interval after the growth spurt (≥93.0% of predicted adult height) (Molinari et al., 2013; Sanders et al., 2017).

Predicted maturation offset as an indicator of the timing of somatic maturation predicts the time before or after an individual experienced peak height velocity (Malina, 2017). Predicted age at peak height velocity is then estimated as CA minus maturity offset. Currently three protocols exist, the Mirwald method (Mirwald et al., 2002), Moore method (Moore et al., 2015), and Fransen method (Fransen et al., 2018), requiring CA, standing height, body mass, sitting height, and leg length (derived from standing height minus sitting height). Age of predicted peak height velocity is then put into context of the current CA to classify an individual as pre-, at- or post-peak height velocity, an indicator of maturity status. Several recent validation studies in longitudinal samples highlighted serious limitations regarding the accuracy of all three predicted maturation offset indicators (Kozieł & Malina, 2018; Malina et al., 2016, 2021; Malina & Kozieł, 2014; Parr et al., 2020; Teunissen et al., 2020). Briefly, these include firstly the large intra-individual variability in the predictions over time; secondly, the dependence of the prediction upon the CA, i.e., age at peak height velocity increased with CA at the time of the prediction, and thirdly, the dependence of the prediction upon maturation status, i.e., predicted ages at peak height velocity were considerable underestimated than observed ages at peak height velocity for early maturing individuals and overestimated for late maturing individuals. These data question the usefulness of predicted maturation offset and age at peak height velocity as a reliable and valid indicator of somatic maturation timing and status.

2.2.2 Biological maturation-related selection bias in youth soccer

Considerable inter-individual variation within single-year CA age groups have been reported during adolescence in youth soccer. Extrema of up to five years difference between the skeletally youngest and oldest player have been shown (Malina et al., 2000). It is well documented that individual differences in biological maturation have a reasonably strong impact upon current physical performance in male youth soccer players (Beunen & Malina, 2007; Meylan et al., 2010). Boys advanced in maturity compared to their less advanced peers are, on average, taller, heavier, and in turn more lean mass resulting in superior strength, power, and speed. Athletes advanced in biological maturation have therefore a potential athletic advantage and are, although still speculative, more likely identified by scouts and coaches and in turn selected into high-performance development programs. For example, among early adolescent soccer players, those who were selected into a professional youth academy were more advanced in skeletal maturity compared to those who remained at the same playing standard who in turn were again more advanced in skeletal maturity than those who dropped out (Figueiredo et al., 2009a). This maturation-related selection bias starts to emerge at the U14 age group which coincides with the onset of puberty and the growth spurt (Hill et al., 2019; Johnson et al., 2017). Most players in the U12 and U13 are on-time with about equal proportions of early and late maturing players, irrespective of the biological maturation indicator used (Malina, 2011). With increasing age through adolescence, proportionally fewer late maturing players are represented in the U14 and following age groups until they eventually are not represented within older age groups (Hill et al., 2019). In contrast, a selection bias favouring early maturing players was observed from the U14 age group onwards and generally increases with CA (Hill et al., 2019; Johnson et al., 2017; Malina et al., 2010). This maturation-related selection bias is of particular concern as talented, yet late maturing soccer players, who are not capable to currently cope with the physical demands might be de-selected from high-performance developmental programs. Consequently, they might lose the exposure to high quality training and competition ultimately limiting the exploitation of their football talent (Cumming et al., 2017). Strategies addressing this biological maturation-related selection bias such as bio-banding training sessions and competitions have been suggested (Cumming, Brown, et al., 2018; Malina et al., 2019). Several other implications arise for various other practitioners such as coaches, scouts, sport scientists, strength and conditioning coaches, sports physiotherapists and psychologists when being faced with players of varying states of biological maturation within their respective age group aiming to maximise performance and health.

2.2.3 Implications of biological maturation in youth soccer

Practitioners working with youth soccer players need to consider the large inter-individual variation in biological maturation within single-ear CA age groups, particularly within the U14 to U17 age groups. Broadly speaking, this pertains, although somewhat linked, the soccer-specific development, injury risk management, and physical development.

As for the soccer-specific development, new concepts such as bio-banding have been implemented into high-performance developmental programs to accommodate maturation-related variation among youth soccer players of the same CA (Malina et al., 2019). This strategy was termed bio-banding and groups youth soccer players into bands based on characteristics associated with growth and biological maturation. Percentage of predicted adult height as an indicator of biological maturation status has been most commonly used grouping players into the bands pre-, at-, and post-peak height velocity (Cumming et al., 2017). Bio-banding is considered as an adjust to CA-based age groups and has been seen as a favourable training strategy by coaches and players to identify and develop talent. Bio-banding training sessions and matches also facilitate the evaluation of a player's talent as variation in biological maturation is less pronounced than in the traditional CA-based age groups (Cumming, Brown, et al., 2018). Several studies investigated the effect of bio-banded tournaments upon physical, technical, tactical, and psychological components (Abbott et al., 2019; Lüdin et al., 2021; Towlson et al., 2021, 2022). Collectively, these studies highlighted only limited to small differences between bio-banded and CA based training formats for physical, technical and tactical parameters. Early maturing players perceived bio-banded training formats as physically and technically challenging, while the opposite was observed for late maturing players, yet they also perceived more opportunities to demonstrate their technical and tactical abilities (Bradley et al., 2019). Indeed, key stakeholders also perceived the psychological aspect as most beneficial when grouping players according to their biological maturation (Reeves et al., 2018). While this might seem counterintuitive as biological maturation does not account for psychological maturation, bio-banding might provide a format for coaches and practitioners to holistically develop youth soccer players by breaking up the routine of traditional CA-based formats and offering new challenges for both early and late maturating players.

As for injury risk management, evidence suggests a clear trend in growth-related injury types throughout maturation with specific injuries being more prevalent during different stages of biological maturation (Monasterio et al., 2021). Specifically, growth-related injuries follow a distal to proximal pattern reflecting the normal sequence of endochondral ossification of the cartilage tissue towards complete bony fusion (Materne et al., 2022; Ogden, 2000). Injury incidence has been shown to be increased during the phase of peak height velocity (Bult et al., 2018; Johnson et al., 2020; Materne et al., 2016). Injury burden is generally highest in the older age groups (i.e., U16 and U17) (Wik et al., 2021), while Osgood-Schlatter disease typically represents the most common apophyseal injury and hip-pelvic apophyseal and muscle injuries result in the largest injury burden particularly during older age groups (Materne et al., 2022). Early maturing players tend to have the greatest overall injury risk and injury incidence of muscle injuries were highest in mature players (Materne et al., 2021). Other studies failed to find differences in injury risk between early-, on-time-, and late maturing youth soccer players (Johnson et al., 2009; Johnson et al., 2020; Le Gall et al., 2007). Although consensus is lacking as to how mitigate injury risk during adolescence, it has been suggested to adjust training load by reducing high neuromuscular load of the players with increased risk and instead varying movement pattern while ensuring sufficient recovery (Wormhoudt et al., 2017). Further, sports physiotherapists and medical doctors should closely monitor musculoskeletal complaints and the current status of biological maturation of the player to identify athletes of potential higher vulnerability and in turn injury risk (Wik et al., 2020). This allows the accurate collection of data while appropriately treating and managing growth-related injuries in youth soccer. Furthermore, strength and conditioning coaches need to consider biological maturation of their players when designing individualised injury prevention programs in relation to the specific areas of the greatest musculoskeletal vulnerability of the youth soccer player.

As for the physical development, sport scientists and strength and conditioning coaches are required to implement training programs for strength, speed and power development in relation to the CA, training age and biological maturation status a youth soccer player (Cumming et al., 2017; Lloyd et al., 2016). Although all physical qualities should be trained during all phases of biological maturation, practitioners need to be aware which training methods is potentially most effective during the different phases of biological maturation (Van Hooren & De Ste Croix, 2020). For example, during periods of rapid growth, particularly during the phase of peak height velocity, some youth soccer players experience temporary disruption of motor coordination suggesting that movement quality during adolescence follows a non-linear pattern (Beunen & Malina, 1988; Quatman-Yates et al., 2012). Consequently, these youth soccer players might have difficulties executing movements that rely on a high level of motor coordination which requires practitioners to appropriately adapt the training plan by prioritising neuromuscular control and proprioceptive exercises (Van Hooren & De Ste Croix, 2020). Similarly, once an athlete experienced the growth spurt, more nuanced and complex strength training methods can be implemented to develop specific aspects of strength, with consideration to the training age and movement quality of the athlete (Myer et al., 2013). Data on the biological maturation status are also used by sport scientists and strength and conditioning coaches as contextual information within the broader scope of an athlete monitoring system (Salter, Croix, Hughes, et al., 2021). Prescribing biologically appropriate training load according to the biological maturation status, while monitoring both the internal training load and acute responses to load practitioners aim to minimise growth-related injury rates and maximise player development (Jayanthi et al., 2022). In this context, biological maturation can be seen as a moderating variable in the relationships between external and internal training load as well as internal training load and associated acute responses to load (Salter, Croix, & Hughes, 2021).

2.3 Training load and psycho-physiological responses to load in youth soccer

The athlete monitoring framework is considered as an important part within the physical training process which aims to maximise sports performance and health of an athlete. The physical training process illustrates the relationship between stimulus, acute and chronic responses to load and sport performance (Jeffries et al., 2021). Within this training process the two constructs of training load and responses to load constitute the athlete monitoring framework. Specifically, training load reflects the systematic repetition of physical training that is actually done and experienced by the athlete. Training load can further be differentiated and quantified using indicators of external (i.e., what the athlete does) or internal (i.e., what the athlete experiences during the exercise) psycho-physiological measures (Impellizzeri et al., 2019). Responses to load are caused and occur after a short (i.e., acute, after a single training session up to a few training sessions) or extended (i.e., chronic, cumulative effects over weeks up to years) period of time and can further be categorised as positive or negative. These responses can be quantified using performance, physiological, subjective, biochemical, and other measures of biological systems that are supposed to be impacted by the preceding stimulus (McLaren et al., 2021).

Practitioners typically aim to target specific biological systems of their athlete's by manipulating the quantity and intensity of the training session. The resulting psycho-physiological responses from these exercise-induced stimuli are then the antecedents of any functional adaptation (Viru & Viru, 2000). Individual characteristics such as chronological age, biological maturity, physical fitness and genetics act as moderating variables influencing this relationship (Impellizzeri et al., 2019). Information on acute and chronic responses to load collected and derived from athletes is commonly used to evaluate the effectiveness of the previous training program as well as to plan and optimize future training load (Salter, Croix, Hughes, et al., 2021; Weston, 2018). The selection of the most appropriate parameters to monitor training load and responses to load in the applied setting should be based on several theoretical, contextual and technical considerations such as the evaluation of measurement properties (i.e., validity, reliability, responsiveness), cost-effectiveness, specificity to the sport, and information required by the practitioners to adapt the training plan (Coutts, 2014; Robertson et al., 2017; Saw, Kellmann, et al., 2016). As the quantification of training load and associated responses to load are considered to be crucial components of athlete monitoring systems the following section aims to provide an overview of these constructs followed by describing individual and contextual factors that influence the responses to load while finishing off with critically appraising the necessary measurement properties of measurement instruments to monitor responses to load.Figure 2.1. Conceptual framework of monitoring the youth soccer player. Adapted from Jeffries et al. (2021). Figure 2.1 summarises and illustrates the conceptual framework of monitoring the youth soccer player.

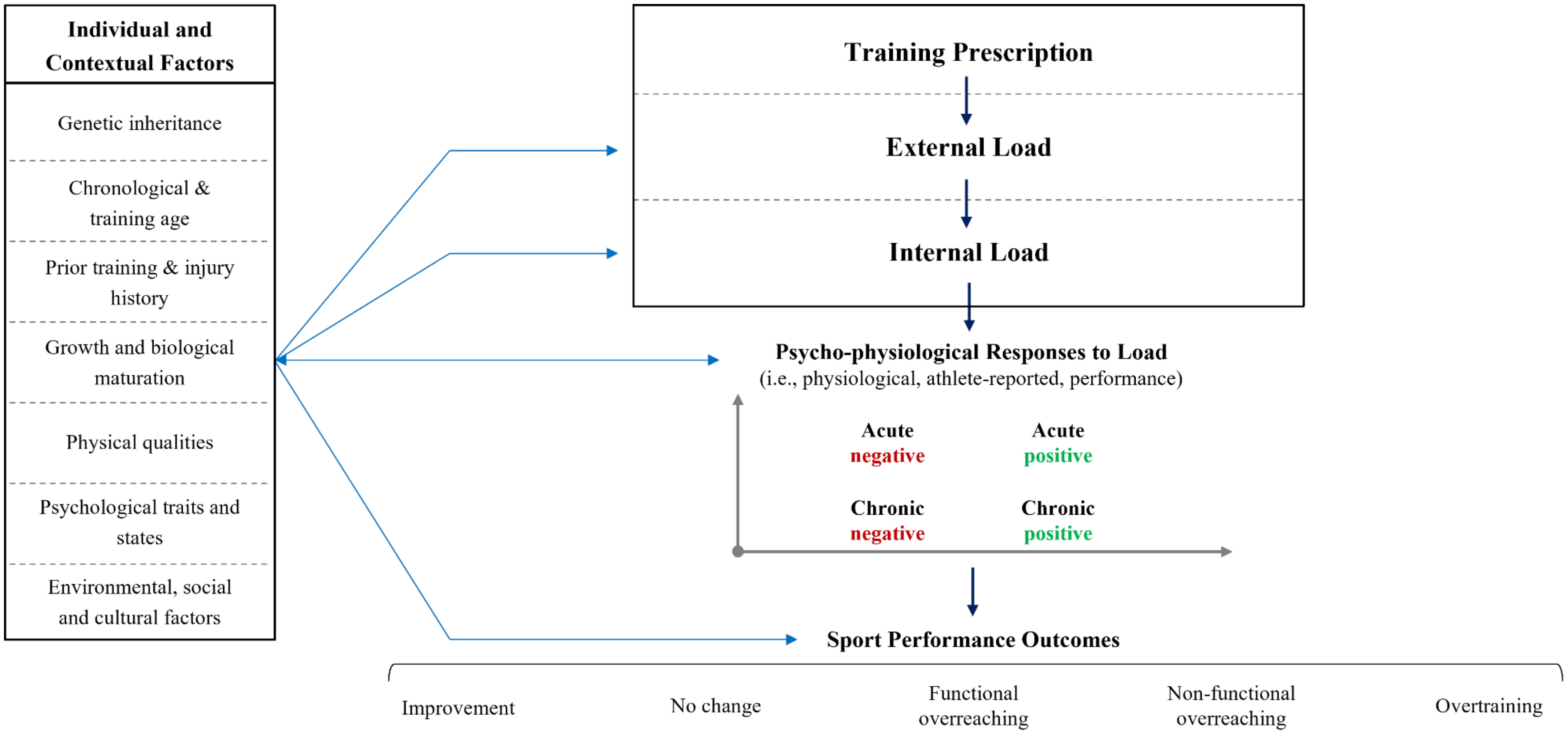

Figure 2.1. Conceptual framework of monitoring the youth soccer player. Adapted from Jeffries et al. (2021).

2.3.1 Monitoring training load

Training load can be described as the input variable and starting point of the framework. Training load can be further described as either external or internal (Impellizzeri et al., 2005). External training load refers to the physical work actually performed by the athlete while internal training load refers to the internal psycho-physiological responses experienced by the athlete during the training session (Jeffries et al., 2021). External training load can be monitored using measures specific to the nature of the sport. Advancements and the increasing adoption of microtechnology in sport has enabled practitioners to systematic monitor external training load in greater depth in training sessions and matches. For example, in team sports such as soccer external training load for field players is typically operationalised by spatial-temporal measures of for example total distance covered, distances covered in specific speed bands, accelerations, and decelerations (Akenhead & Nassis, 2016; Salter, Croix, Hughes, et al., 2021). In contrast, for goalkeepers external training load is typically measured by the number of jumps, dives, and change of directions (Malone et al., 2018; White et al., 2018). In contrast, in sports such as weightlifting, indicators of external load encompass the weight lifted, time under tension or total work (i.e., force x displacement) (B. R. Scott et al., 2016). Regardless of the measures used to objectively quantify the external training load, practitioners typically plan and prescribe the organisation, volume and intensity of a given exercise, drill or training session according to external training load measures aiming to elicit the desired psycho-physiological response. As such, internal training load can be monitored using psychological and physiological measures (Jeffries et al., 2021). Importantly, the biomechanical stress and strain experienced by bodily tissues in response to external forces although difficult to actually quantify can also be categorised as internal training load (Vanrenterghem et al., 2017). In the context of soccer, subjective perceptions of effort or exertion are widely monitored (Halson, 2014). Subjective perceptions can be quantified using a rating of perceived exertion (RPE) by assigning a numeric value to the perceived exertion at a given time point (Borg, 1998). When athletes recall their RPE following the entire training session or match, as typically performed in soccer, it is termed session RPE (sRPE) and represents a measure of internal training intensity (Foster et al., 2001, 2021). To compute a single measure of internal training load, sRPE can be multiplied by the volume of the training session or competition derive sRPE training load (sRPE-TL) (McLaren et al., 2021). This enables practitioners to compute a global measure across different types of training and competition modalities. However, this also highlights a limitation of this method as it might not reflect the structure specific internal loads experiences of specific structures (McLaren et al., 2018). Several validated scales can be used to measure RPE with the Borg's Category-Ratio 10 (deciMax; CR10®) and Category-Ratio 100 scale (centiMax; CR100®) being the two most widely used versions in soccer (Haddad et al., 2017; McLaren et al., 2021). Recording heart rate is another common way to measure internal training load intensity (Akenhead & Nassis, 2016). To derive one global measure of internal training load the training impulse (TRIMP) can be computed which is the product of the intensity as calculated by the average heart rate through the heart rate reserve method, duration of the training session or competition and a weighting factor based on blood lactate profiles observed during graded maximal exercise test (Banister, 1991). Several modifications to this original method have been proposed using different arbitrarily (Edwards, 1992; Lucia et al., 2003) or individual weighting factors (Manzi et al., 2009). Limitations exist however when aiming to measure the internal training load for intermittent sports as the average heart rate does not reflect the fluctuations associated with the intermittent activity profile of soccer. In addition, loss of data due to connectivity issues is another limitation when aiming to accurately monitor heart rate in contact and invasion sports. Other measures of internal training load include physiological parameters such as $\dot{V}O_2$ kinetics, blood lactate concentration or sweat rate (Halson, 2014). However, the collection of such data is often perceived as inconvenient in the applied setting and therefore less common.

The internal training load experienced by an athlete may vary depending on several individual and contextual modifiable and non-modifiable factors such as genetics, training status, biological maturity, and nutritional intake (Impellizzeri et al., 2019). As such, the same external load may result in individual athletes experiencing a different internal load. Similarly, as modifiable (e.g., training status) and contextual factors (e.g., heat) may change throughout a given period, the individual internal load may also change accordingly for an individual athlete. Importantly, it is this individual internal load that affects the acute psycho-physiological response ultimately drives the functional adaptations of training.

2.3.2 Psycho-physiological responses to load

Psycho-physiological responses to load can be described as a broader construct that occur after a single or a number of training sessions (Jeffries et al., 2021). Depending on the time frame required to elicit the psycho-physiological responses they can be classified as either acute or chronic. Clearly, responses cannot be dichotomised into two distinct categories but rather should be seen as continuous conditions after a short and extended period of time. Nevertheless, psycho-physiological responses occurring after a single or after a few training sessions can be operationalised as acute. This resembles the time frame of a typical microcycle in soccer whereby one or two training sessions early in the microcycle are dedicated to eliciting substantial psycho-physiological responses (Kelly et al., 2020; Stevens et al., 2017).. Depending on the magnitude of the stimulus the response pattern can vary from a few minutes up to 72 h after a single training session to return back to baseline (Silva et al., 2018). A short taper of reduced training load towards the end of the week then allows the impaired training responses to disappear and return back to baseline (Sands et al., 2017). Assessing psycho-physiological responses immediately or 24 hours after a match to accommodate recovery strategies is another aspect of acute and not chronic responses to load. As such, acute psych-physiological responses to load are mainly monitored to evaluate how an athlete copes during and after a short, intensified training or competition period to avoid subsequent maladaptation. The cumulative responses occurring after an extended period of training such as weeks, months, and years can be operationalised as chronic. Quantifying psycho-physiological responses over time allows practitioners to evaluate acute trends (i.e., transient training response) and if these acute trends develop into more chronic conditions if a short recovery period of a few days does not allow the return to a previously established baseline.

Psycho-physiological responses to load can also be classified as positive or negative indicating responses that either improve (i.e., positive) or impair (i.e., negative) the actual sports performance. Similar to acute and chronic, positive and negative psycho-physiological responses can be conceptualised as existing on a continuum ranging from a transient state of functional adaptation to tissue overload and (non-functional) overtraining (Kellmann et al., 2018; Vanrenterghem et al., 2017; Weakley et al., 2022). Both positive and negative responses to load can occur at the same time highlighting the complexity of interpreting psycho-physiological responses to load that can be derived from the multitude of different measurement instruments (Norris et al., 2021).

2.3.3 Monitoring acute psycho-physiological responses to load

The quantification of acute psycho-physiological responses to load is challenging as there is, despite its crucial component within the athlete monitoring framework, no established gold standard with regards to measurement instruments (Impellizzeri et al., 2019). Instead, acute psycho-physiological responses are quantified by surrogate measurement instruments. As the acute psycho-physiological response to load encompasses the complex interaction of multiple domains of the human body including but not limited to the cardiorespiratory, metabolic, neuromuscular, biochemical, endocrine, and musculoskeletal system, practitioners typically select several measurement instruments.

The selection of the most appropriate measurement instruments depends on several key aspects such as specificity to the sport, scalability and time efficiency when administered to large groups of athletes as well as theoretical aspects such as measurement properties (i.e., reliability, validity, responsiveness, see section 2.3.5 below) (Coutts, 2014; Robertson et al., 2017; Starling & Lambert, 2018; Thorpe et al., 2017). In addition, the selection should also be based on the information required by the practitioners to adapt the training prescription and in turn training load for the subsequent training sessions. For example, given the widespread adoption of sided-games (i.e., modified games of short durations, played on reduced pitch dimensions involving fewer players) by soccer coaches within the weekly training structure (Sarmento, Clemente, et al., 2018), coaches may want to receive detailed information regarding the neuromuscular and cardiorespiratory demands of specific sided games. As such, specific metrics that aim to quantify the acceleration, deceleration and change of direction load through athlete tracking technologies (Ellens et al., 2022; Torres-Ronda et al., 2022) might be selected to describe the intensity in relation to the qualitative analysis of the technical and tactical requirements of the sided game.

Recent technological advancements in the area of wearables have substantially increased the opportunity to quantify acute responses from various biological systems (Cardinale & Varley, 2017). Broadly speaking, these can be classified into three categories ranging from physiological parameters to performance-based parameters and more complex and integrated athlete-reported parameters (Wilson & Cleary, 1995).

Physiological measurement instruments can be considered as the most fundamental parameters as they focus on the function of specific cells and organ systems (Heidari et al., 2018). Various physiological parameters may be suitable to monitor acute responses to load such as hormones, neurotransmitters, proteins, metabolites, cardiac autonomic nervous based parameters (Greenham et al., 2018). The most commonly used parameters are creatine kinase, testosterone and cortisol (Doeven et al., 2018). Creatine kinase provides information on the magnitude of muscle damage caused by intense and prolonged muscular training including eccentric or unaccustomed exercise (Brancaccio et al., 2007). There is a high degree of variability among and within individual athletes (Julian et al., 2017) highlighting the need to individualise the assessment of acute responses of physiological parameters. Testosterone and cortisol derived from either saliva or blood samples reflect the balance between anabolic (e.g., protein and muscle glycogen synthesis) and catabolic processes (e.g., protein breakdown, suppression of immune function) (Hayes et al., 2016). While data for testosterone and cortisol in response to periods of increased training load are equivocal, substantial increases have been documented after strenuous and prolonged activities such as soccer matches (Doeven et al., 2018; Greenham et al., 2018; Hagstrom & Shorter, 2018). However, the implication of increased levels of creatine kinase upon physical performance such as sprint performance is still unknown. Although the collection of those parameters does not interfere with training or adds further load upon the athletes, the need for specialised equipment, required time and their invasiveness often limits their practical implementation in applied high-performance programs.

Other physiological parameters such as exercise heart rate during (HRex) and after submaximal runs (HRR), resting heart rate (rHR) or resting heart rate variability (HRV) have been widely used to monitor acute responses of cardiac parasympathetic activity to load (Bellenger et al., 2016; Shushan et al., 2022; Stanley et al., 2013). As a non-invasive and time-efficient measurement instrument, these parameters can easily be collected for large groups of athletes in practical settings. However, changes in these parameters always need to be interpreted in conjunction with the current training phase (i.e., accumulated training load) in addition to athlete-reported parameters related to stress and recovery to contextualise acute responses as either positive or negative (Bellenger et al., 2016; Le Meur et al., 2013). In addition, several moderating variables might acutely influence heart rate and hence the above mentioned parameters such as environmental (e.g., heat, altitude, noise) and lifestyle (e.g., sleep, alcohol consumption) factors (Schneider et al., 2018). Despite these difficulties in accurately interpreting acute responses in HRex, HRR, rHR and HRV, there has been growing popularity among practitioners to monitor the autonomic nervous system and hence to guide the training process (Thorpe et al., 2017). Recent findings highlighted the potential utility of regularly measuring these simple parameters during short periods of increased training load to infer on acute responses of the cardiac parasympathetic system (Bosquet et al., 2008; Buchheit, 2014; Daanen et al., 2012; Plews et al., 2013). Importantly, the physiological mechanisms underlying the cardiac autonomic responses to load, although not fully understood, differ among the parameters (e.g., meta-boreflex activity for HRR vs. exercise-induced plasma volume for HRex (Buchheit, Al Haddad, et al., 2009)) which highlights that these parameters provide distinct information of the cardiac autonomic system. Less frequently used examples of physiological parameters to monitor acute response to load include the assessment central and peripheral levels of activation through electrical or magnetic stimulation.

The use of athlete-reported parameters withing the athlete monitoring framework has increased substantially within recent years (Taylor et al., 2012; Thorpe et al., 2017). While historically the interest to implement athlete-reported measurement instruments was to detect early symptoms of overtraining, the emphasis has shifted towards optimising training adaptations to guide the training process (Morgan et al., 1987; Saw, Kellmann, et al., 2016). Athlete-reported instruments encompass measures or questionnaires used to assess individually perceived responses to load of a specific underlying, unobservable construct such as recovery, fatigue, pain and soreness (Jeffries et al., 2020). These can broadly be described as physical symptoms of the training response, while sport psychologists should be consulted when aiming to implement and monitor psychologically oriented measurement instruments. Athlete reported measurement instruments seem to provide a higher consistency and responsiveness than other objective physiological and performance-based parameters in relation to acute and chronic training loads (Saw, Main, et al., 2016). Among athlete-reported measurement instruments specifically developed for athlete populations, the Recovery Stress Questionnaire for Athletes (RESTQ-Sport) with its derivatives Acute Recovery and Stress Scale (ARSS) and the Short Recovery and Stress Scale (SRSS) and the Multi-Component Training Distress Scale (MTDS) are the most commonly used and validated multi-item and multi-dimensional instruments (Jeffries et al., 2020; McLaren et al., 2021). The original RESTQ-Sport consists of 77 items with a total of 19 scales that reflect the two constructs of recovery and stress regarding the previous three days and nights (Kallus & Kellmann, 2016; Kellmann & Kallus, 2001). A shorter, abbreviated version of the RESTQ-Sport, the RESTQ-Sport-36 has recently been developed encompassing 36 items with a total of 12 scales as a more user-friendly version that can be implemented more regularly within the athlete monitoring framework (Kellmann & Kallus, 2016). The ARSS consists of 32 items and includes eight scales (of four items) reflecting the two constructs of recovery (physical performance capability, mental performance capability, emotional balance, overall recovery) and stress (muscular stress, lack of activation, negative emotional state, and overall stress) (Kellmann & Kölling, 2020). Modified versions of the ARSS for children and adolescents from 10 to 15 years of age have been developed to facilitate the understanding of the descriptive adjectives of the respective items (Kölling et al., 2019). However, these measurement instruments are often considered as time-consuming preventing their implementation on a daily basis for a large group of athletes. Therefore, the SRSS has been developed, measuring the same constructs as the RESTQ-Sport and ARSS, recovery and stress, using only eight scales as single items (Kellmann & Kölling, 2020). The SRSS has also been modified for children and adolescents by adding a sentence to describe the respective item (Kölling et al., 2019), however, validity and reliability are not compromised when using the original SRSS with children and adolescents. Finally, the MTDS consists of 22 items measuring a variety of constructs such as depression, vigour, physical symptoms, sleep disturbances, perceived stress, and fatigue (Main & Grove, 2009). Because of their simplicity, good face validity and ease of use, single-item instruments are widely used in the practical setting (Jeffries et al., 2021; Thorpe et al., 2017). The so-called wellness-items based on the work of Hooper and Mackinnon (1995) and (Hooper et al., 1995) (e.g., fatigue, sleep quality, muscle soreness, stress, enjoyment of training, irritability, health causes of stress, and unhappiness) are most commonly used, although several modifications (e.g., adding or removal of items) have been made without justification (Jeffries et al., 2020). In addition, these single items have not been sufficiently validated as they are inherently multi-dimensional and complex in nature. Furthermore, there is a lack of a clear definition and hence framework of the higher-order construct that these items are supposed to measure. Taken together, the implementation of these so-called wellness-items for both research and practice should be taken with caution, until proper validation is carried out (Jeffries et al., 2020).

Performance-based parameters are parameters that are related to the competitive performance or measure a specific physical quality such as strength, speed or endurance tests. Maximal performance testing is considered to be the gold standard for identifying positive and negative responses to load. However, given the additional load and time constraints associated with such testing procedures, they are often considered as unsuitable for use in high-performance programs and therefore less exhaustive and submaximal measurement instruments are adopted instead (Thorpe et al., 2017). Various vertical jump protocols such as the squat jump, countermovement jump (CMJ), and drop jump have been used in both research and practise (Jeffries et al., 2021; Ryan et al., 2020; Taylor et al., 2012). The CMJ is the most commonly used measurement instruments, likely due to the widespread availability of force plate systems in high-performance programs. A multitude of variables can be derived from force-time data of a CMJ and is has been suggested that variables reflecting kinetics (e.g., force at zero velocity) and kinematics (e.g., countermovement depth) of the different phases of the jump providing the most promising insights into the underpinning neuromuscular mechanism to monitor acute neuromuscular responses to load (Fitzpatrick et al., 2019; Gathercole et al., 2015). Similar to other performance-based parameters, the CMJ can be used to monitor both acute responses to load after a few days of accumulated training load and chronic responses by evaluating the effectiveness of a training block upon lower body power development. While several studies in professional senior team sports showed the potential usefulness of kinetic and kinematic variables to monitor acute responses to load (Cormack, Newton, & McGuigan, 2008; Rowell et al., 2017; Ryan et al., 2019), limited data exist in high-level youth populations. Other examples of performance-based measurement instruments to monitor acute responses to load are maximal strength tests (e.g., isometric mid-thigh pull (Norris et al., 2019)), sprint tests (e.g., 30 m sprint time (Marrier et al., 2016)), and cycle-ergometer tests (e.g., 6 s sprint test (Roe et al., 2017).

2.3.4 Individual and contextual factors influencing the acute and chronic responses in youth soccer

Individual factors are characteristics such as the genetic inheritance, chronological and training age, and prior training and injury history of an athlete. In contrast, contextual factors refer to environmental conditions, and social and cultural factors that lay outside the actual training process(Coles et al., 2017; Jeffries et al., 2021). Regardless of whether they are individual or contextual factors, they moderate all components of the training process. The arrows indicate the potential causal pathways of influence. For example, the internal training load an athlete experiences during a given external load varies in relation to the individual and contextual factors. Exposure to hypoxia or heat are contextual factors eliciting substantially higher levels of perceived exertion and lower oxygen saturation during the exercise (Deb et al., 2018; Levine & Buono, 2019). Similarly, biological maturity can act as a moderating factor influencing the internal training load and acute neuromuscular responses to load after a standardised bout of external load (Salter, Croix, & Hughes, 2021). The bi-directional arrow between individual and contextual factors and the psycho-physiological responses to load indicates the reciprocal relationship between both components. For example, large acute, negative psycho-physiological responses to load after an intensified period of load can act as individual factors potentially influencing the subsequent internal training load in the next training session or match. While some individual and contextual factors are modifiable (nutritional status, environmental conditions, recovery strategies, etc.), others are non-modifiable (e.g., genetics, training age, etc.). Growth and maturation can be considered as largely non-modifiable as a very large proportion of variance is genetically inherited with the remaining proportion originating in the environment (e.g., dietary and medical restriction, severe psychological stress, and socioeconomic class) (Malina, Bouchard, et al., 2004; Rogol, 2016).

2.3.5 Evaluating the measurement properties of measurement instruments to monitor psycho-physiological responses to load

Before measurement instruments to monitor psycho-physiological responses to load can be confidently implemented within an athlete monitoring framework, several measurement properties need to be critically evaluated. This allows practitioners to apply a measurement instrument with greater confidence in the data generated. There are three domains of measurement properties: validity, reliability, and responsiveness (Mokkink et al., 2010; Robertson et al., 2017).

Validity refers to the degree to which a measurement instruments measures the construct it purports to measure (Mokkink et al., 2010; Vet et al., 2011). Validity includes several measurement properties such as criterion validity (i.e., the degree to which the scores of a parameter are an adequate reflection of an established gold standard) and construct validity (i.e., the degree to which the scores of a parameter are consistent with hypotheses based on the assumption that the parameter validly measures the construct to be measured). Construct validity includes the sub-types convergent validity (i.e., the degree to which two parameters of a theoretical construct that theoretically should be related, are in fact related) and discriminant validity (i.e., the degree to which two parameters of different constructs that theoretically should not be related, are in fact not related).

Reliability refers to the extent to which the scores of a parameter for athletes who have not changed are the same for repeated measurement under several conditions (Mokkink et al., 2010; Streiner et al., 2015). Establishing the measurement error through test-retest measurements provides references values for the systematic and random error of an athlete’s score for a given parameter of the construct to be measured. To calculate such reference values for parameters that are beyond measurement error the smallest detectable change (SDC) can be computed (Vet et al., 2011). These reference values are, however, specific to the population of interest. Currently, there is a paucity of data establishing the measurement error of measurement properties aiming to assess responses to load within youth soccer players of different maturity status. It is therefore crucial that such information is available for both researcher and practitioners working with adolescent soccer players to assist in detecting meaningful changes in parameters monitoring acute psycho-physiological responses to load.

Responsiveness refers to the ability of a parameter to detect change over time in the construct to be measured (Mokkink et al., 2010) and has been considered as the most important property of measurement instruments (Terwee et al., 2003). Two different approaches are available for assessing responsiveness: a criterion approach and a construct approach (Vet et al., 2011). For the criterion approach an established gold-standard measurement instrument is required. As there is no gold-standard measurement instrument to quantify the construct of acute psycho-physiological responses to load, a construct-based approach has to be adopted instead. To do so, repeated measurements from athletes under different conditions in which different acute responses to load are expected. For example, large changes in acute responses after a match or an intense training session can be expected for those players who accumulated and experienced more external and internal loads, respectively. In contrast, after one or two days of rest, trivial to small changes in acute responses should be evident serving as a viable reference. Responsiveness can then be assessed by comparing by i) comparing the acute responses after high vs low load days, and ii) assessing the relationship between accumulated training load and acute responses with the higher the relationship the greater the responsiveness for a given measurement instrument (Vet et al., 2011).

Only few studies have investigated the reliability and responsiveness of commonly used measurement instruments in youth soccer players (Buchheit et al., 2018; Evans et al., 2022; Fitzpatrick et al., 2019; Malone, Murtagh, et al., 2015; Noon et al., 2015; Pelka et al., 2018; Salter, Croix, & Hughes, 2021; Sawczuk et al., 2018b). In addition, previous studies were predominately conducted with soccer players during the late adolescence, i.e., from 16 to 19 years of age. As these players can likely be classified as post-pubertal (i.e., after the growth spurt), results cannot be transferred to less mature players (i.e., pre- and circa-pubertal players) given the large and non-linear psychological, physiological, neuromuscular, and motor control changes players experience throughout adolescence (Beunen & Malina, 2007; Ratel & Martin, 2015). Thus, responses to load may be maturity-dependent in a way that pre-pubertal athletes show smaller responses to load than early and late adolescent athletes (Ratel & Williams, 2017). In addition, during period of accelerated growth, particularly during the growth spurt athletes often experience temporary disruptions in motor coordination (Lloyd et al., 2012; Quatman-Yates et al., 2012). Thus, less mature athletes possess a less efficient movement strategy, particularly during rapid movements that rely on the stretch-shortening cycle potentially impacting the reliability in relation to the biological maturation status. As any measurement instrument that is used in both research and practice should provide valid and meaningful information, a critical appraisal of the key measurement properties is imperative. This information allows practitioners and researcher to make more informed decisions when monitoring acute psycho-physiological responses to load of commonly used measurement instruments to guide the overall training process in order to maximise health and performance.

Chapter 3: Research Aims and Objectives

While there has been considerable research interest in the area of athlete monitoring over the past decade, most of the knowledge stems from senior professional team sport populations. Whether or not this established knowledge can be transferred to the adolescent athletes remains widely unknown. Therefore, the overall aims of this thesis were to advance the field of applied research in high-level soccer by firstly comparing a new device measuring skeletal age to a previously established method of percentage of predicted adult height as two potential practical, non-invasive methods to assess biological maturation status and subsequently evaluating the reliability and responsiveness as two key measurement properties of commonly used measurement instruments that aim to assess acute psycho-physiological responses to load of youth soccer players. These aims were addressed by four experimental studies, which had the following specific study aims.

Study I

Construct validity of percentage of predicted adult height and BAUS skeletal age to assess biological maturity in academy soccer.

Aim: To firstly establish the construct validity of the BAUS^{TM} system measuring skeletal age and percentage of predicted adult height based on the Khamis-Roche method to assess the construct of biological maturation status and secondly examine the maturity-related selection bias across the U12 to U17 age groups.

This aim was addressed in Chapter 4.

Study II

Poor reliability of measurement instruments to assess acute responses to load in soccer players irrespective of biological maturity status.

Aim: To assess the short-term between-day reliability of commonly used measurement instruments to assess and monitor acute psycho-physiological responses to load in youth soccer players in relation to biological maturation status.

This aim was addressed in Chapter 5.

Study III

Are measurement instruments responsive to assess acute responses to load in high-level youth soccer players?

Aim: To assess the short-term responsiveness of measurement instruments aiming to quantify the acute psycho-physiological response to load in high-level youth soccer players.

This aim was addressed in Chapter 6.

Study IV

Psycho-physiological responses to a pre-season training camp in high-level youth soccer players?

Aim: To examine the time-course and in turn short-term responsiveness of psycho-physiological responses to a short intensified pre-season training camp in high-level youth soccer players.

This aim was addressed in Chapter 7.

Chapter 4: Construct validity of percentage of predicted adult height and BAUS skeletal age to assess biological maturity in academy soccer

This study has been accepted for publication following peer review in the journal *Annals of Human Biology*. The content has been reformatted for the purposes of this thesis. The full reference details of this published study are:

Construct validity of percentage of predicted adult height and BAUS skeletal age to assess biological maturity in academy soccer

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4.1 Abstract

Background: The assessment of biological maturity status plays an important role in talent identification and development programs.

Aim: To compare age at predicted adult height and BAUS skeletal age as indicators of biological maturity status in youth soccer players using a construct-validity approach.

Subjects and methods: Participants were 114 players from the U12 to U17 age groups of a professional youth soccer academy. Maturity status was determined via percentage of predicted adult height based upon the Khamis-Roche method (somatic maturity) and assessed via the SonicBone BAUS^{TM} system (skeletal maturity). Convergent and known-groups validity were evaluated between maturity assessment methods and by comparing maturity-related selection biases across age groups.

Results: Although maturity status indicators were largely interrelated ($r=0.94$, 95%CL 0.91 to 0.96), concordance ($\kappa=0.31$ to 0.39) and spearman's rank-order correlations ($\rho=0.45$ to 0.52) of classification methods were moderate. A selection biases towards early maturing players emerged in the U14 which remained relatively consistent through to the U17 age group.

Conclusion: Results confirm the construct-validity of both methods to assess biological maturity status although further validation relative to established indicators of biological maturity is needed. Furthermore, caution is also warranted when interpreting maturity status classification methods interchangeably given the poor concordance between classification methods.

Keywords: maturation, adolescence, skeletal age, percentage adult height, validation

4.2 Introduction

Several multidimensional and comprehensive talent identification models have been proposed, detailing the inter-relationship of potential predictors for future sports performance (Vaeyens et al., 2008). Such models typically take growth and maturation characteristics of youth athletes into consideration offering a more strategic approach to talent identification, selection and development (Cumming et al., 2017). Biological maturation refers to the progress towards maturity within each biological system and can be assessed in terms of status (level of maturation at the chronological age (CA) of observation), timing (CA at which specific maturational events occur), and tempo (rate at which maturation progresses) (Malina et al., 2015). Children and adolescents of the same CA can vary substantially in terms of both maturity status and timing (Coelho-e-Silva et al., 2010; Malina et al., 2010). Objective and valid protocols to assess biological maturity are therefore required to inform and guide key stakeholders upon talent identification and selection strategies.

The assessment of biological maturity typically includes indicators of the skeletal, sexual, somatic and dental system (Malina et al., 2015). As all tissues and organ system mature at different times and rates, biological maturity varies with the respective system considered (Beunen et al., 2006a). Although, skeletal maturity is widely recognized as the best indicator of maturity status (Acheson, 1966), no single method can be ascribed as the ‘gold standard’ of maturity (Malina et al., 2015). All indicators of the construct maturity status are, on average, highly interrelated during adolescence (i.e. about 10 through 16 years of age) allowing for comparisons being made between different maturity status indicators (Beunen et al., 2006a; Bielicki et al., 1984). In practise, these indicators reflecting the construct of maturity status have to be both acceptable with regard to costs and ethical issues and scientifically sound in terms of measurement properties.

Commonly used and clinically established indicators of maturity status are skeletal age (SA) and secondary sex characteristics (breasts, genitals, pubic hair) (Malina et al., 2015). SA is determined by evaluating a standard radiograph of the hand-wrist bones by qualified personnel (Malina et al., 2015). Exposure to a low dose of radiation and logistical difficulties (e.g., expenses, trained and experienced assessors, time constraints of the athlete) complicate the application of this technique as a regular assessment tool in applied sports environments. Non-invasive methods to estimate maturity status through somatic maturity indicators have therefore gained popularity. Two commonly used methods are the calculation of predicted maturity offset before age at peak height velocity (PHV) (Mirwald et al., 2002) and the calculation of percentage of predicted final adult height (Roche et al., 1983). Recent longitudinal studies highlighted limitations of the maturity offset method warranting care in its application (Malina et al., 2015). Several equations to predict final adult height without an estimate of SA have been validated previously, including the Khamis-Roche method (Coelho-e-Silva et al., 2010; Khamis & Roche, 1994), Roche-Wainer-Thissen method (Roche et al., 1983) and the Beunen-

Malina method (Beunen et al., 1997). Percentage of predicted adult height based on the Khamis-Roche method showed reasonable concordance with maturity status classifications based on SA in youth American football (Malina, Dompier, et al., 2007), soccer (Malina et al., 2012), roller hockey (Coelho-e-Silva et al., 2010), and tennis players (Myburgh et al., 2019) demonstrating the construct validity of percentage of predicted adult height as indicator of maturity status. As SA and percentage of predicted adult height reflect different domains, yet related, aspects of the construct biological maturity status (skeletal vs. somatic) the adoption of both types of indicators might provide additional insight into the maturity profile of an athlete. This highlights the need for more practical protocols to assess skeletal maturity for coaches and researchers alike to complement the already established and commonly applied somatic indicators (e.g., percentage of predicted adult height based on the Khamis-Roche method).

To address the above mentioned limitations associated with the traditional SA assessment protocols, the non-invasive portable BAUS^{TM} system (SonicBone Medical Ltd., Israel), was developed using quantitative ultrasonographic technology to estimate SA. Briefly, this devise automatically computes the skeletal age by analysing the speed of propagation through bone of high frequency waves of a short ultrasound pulse and the reduction in amplitude of this ultrasound pulse at three sites of the left hand (Rachmiel et al., 2017). To our knowledge, the device has only been validated in comparison to SA derived from standard radiographs of the hand-wrist bones using the Greulich and Pyle method in a group of 150 male and female 4 to 17 year old patients (10.6 ± 3.3 years, standing height and body mass were not provided) of a pediatric endocrinology clinic (Rachmiel et al., 2017). They found no significant bias in skeletal age between assessment methods. In order to apply this device with confidence in elite youth soccer, it is necessary to investigate the convergent validity of this method against previously established practical and commonly used indicators of maturity in this population.

Previous research has shown that a selection gradient towards early maturing athletes is evident in youth soccer. This bias starts to emerge from 12 to 13 years of age and tends to increase with CA (Cumming, Searle, et al., 2018; Figueiredo et al., 2009a; Hill et al., 2019; Johnson et al., 2017). Children and adolescents of the same CA can vary substantially in terms of both maturity status and timing (Coelho-e-Silva et al., 2010; Malina et al., 2010). Athletes advanced in biological maturity for their age tend to be, on average, taller and heavier, show superior athletic capabilities (i.e. greater size, strength, speed and power) and are more likely to be selected and recruited into professional academies (Johnson et al., 2017; Meylan et al., 2010). The ability to discriminate between a group of individuals known to differ in a particular characteristic (i.e. known-group validity) is an important quality criteria for measurement properties of construct validity (Prinsen et al., 2016). Therefore, replicating the same pattern and magnitude for maturity-related selection biases in a different sample of youth soccer players (Hill et al., 2019; Malina, Dompier, et al., 2007; Malina et al., 2012; Myburgh et al., 2019) would further provides support for the construct validity of the BAUS^{TM} system and percentage of predicted adult height to assess biological maturity status.

In light of the previous discussion, the purpose of this study was to establish the construct validity of the BAUS™ system and percentage of predicted adult height based on the Khamis-Roche method to assess the construct of biological maturity status. Our first aim was to evaluate the convergent validity of the BAUS™ system to estimate the maturity status relative to percentage of predicted adult height derived from the Khamis-Roche method in a German professional soccer academy. Based on observations in youth tennis (Myburgh et al., 2019) and soccer (Malina et al., 2012) using standard radiographs as an indicator of skeletal maturity, it was hypothesised that despite large agreement for maturity status estimates, concordance of maturity timing classifications would be poor to moderate. Our second aim was to determine the known-group validity of both methods by examining the magnitude of maturity-related selection biases across age groups. It was hypothesised that maturity-related biases coincide with the onset of puberty and increases with chronological age for both methods.

4.3 Methods

4.3.1 Participants

In total, a convenience sample of 114 male youth soccer players (age: 14.2 ± 1.7 years, standing height: 166.3 ± 13.0 cm, body mass: 57.4 ± 14.5 kg, of European ancestry n = 95, African n = 10, Middle Eastern n = 9) from an accredited elite youth soccer academy in Germany agreed to participate in this study. Players were selected by the academy based on current sport-specific qualities and future potential in terms of technical, tactical, social and physical skills. Participants were selected from the Under 12 (U12) to U17 age groups as these age groups included players from different stages of biological maturity (i.e., pre-pubescent; pubescent, post-pubescent). This sample is representative of adolescent athletes involved in youth sports as previous research indicated advanced maturity levels across several other sports, consistent with data in youth soccer (Malina, 2011). Data were collected before training sessions over the course of four weeks during the first half of the season as part of the regular anthropometry assessment (October/November 2019). Upon enrolment of each player, parents/guardians signed contracts providing consent and assent confirming that data arising as a condition of regular player monitoring procedures can be used for research purposes. The study was approved by the institutional ethics committee and was conducted according to the Declaration of Helsinki.

4.3.2 Procedures

4.3.2.1 Biological maturity

Standing height (± 0.1 cm; KERN MPE, KERN & SOHN GmbH, Balingen, Germany) and body mass (± 0.1 kg; KERN MPE, KERN & SOHN GmbH, Balingen, Germany) were measured by accredited academy physiotherapists using standardised procedures according to the International Society for the Advancement of Kinanthropometry (ISAK) guidelines (Stewart et al., 2011). Percentage of predicted adult height attained at the time of the observation was used as a measure of somatic maturity status (Roche et al., 1983). Owing to the invasiveness and logistical constraints associated with the assessment of standard radiographs, percentage of predicted adult height has been selected as this method has been adopted by practitioners across various sports (Cumming et al., 2017). Although this prevents to follow a criterion-based validity approach, it allows the comparison of practically used methods to assess the biological maturity in applied sport settings. The Khamis-Roche method was used to predict the adult height of each participant using the participant's standing height, body mass, chronological age at observation and self-reported mid-parental standing height (Khamis & Roche, 1994).

Table 4.1. Descriptive data (mean ±SD) regarding biological maturity for each age group (n = 114).

Variable	**U12 (n = 18)**	**U13 (n = 15)**	**U14 (n = 17)**	**U15 (n = 20)**	**U16 (n = 22)**	**U17 (n = 22)**	**Total (n = 114)**
CA (years)	11.4 ± 0.3	12.6 ± 0.3	13.5 ± 0.2	14.6 ± 0.3	15.5 ± 0.4	16.5 ± 0.4	14.2 ± 1.8
Standing height (cm)	146.4 ± 6.2	153.5 ± 6.6	167.0 ± 8.3	171.1 ± 5.8	177.9 ± 6.6	174.7 ± 6.6	166.3 ± 13.0
Body mass (kg)	37.3 ± 6.2	41.3 ± 5.1	56.6 ± 9.4	61.2 ± 7.4	69.0 ± 7.5	70.3 ± 7.3	57.4 ± 14.5
SA (years)	11.3 ± 1.1	12.8 ± 1.0	14.9 ± 1.4	15.8 ± 1.0	17.2 ± 1.1	17.0 ± 0.9	15.1 ± 2.4
SA-CA (years)	-0.1 ± 1.1	0.2 ± 1.1	1.4 ± 1.3	1.2 ± 1.1	1.7 ± 0.9	0.5 ± 1.0	0.9 ± 1.2
Predicted adult height (cm) SonicBone™	178.7 ± 4.7	177.5 ± 4.2	181.2 ± 3.4	176.8 ± 2.8	179.9 ± 4.4	177.7 ± 4.4	178.6 ± 4.2
Predicted adult height (cm) Khamis-Roche	178.4 ± 6.7	177.4 ± 6.2	180.8 ± 6.4	179.8 ± 4.9	181.8 ± 5.4	177.3 ± 7.0	179.4 ± 6.3
Percentage predicted adult height (cm)	82.0 ± 1.7	86.4 ± 1.9	92.1 ± 3.3	96.8 ± 2.6	98.9 ± 1.9	98.3 ± 1.4	93.1 ± 6.7
z-score predicted adult height	0.16 ± 0.68	-0.04 ± 0.58	0.75 ± 0.67	0.36 ± 0.50	0.67 ± 0.31	0.53 ± 0.28	0.43 ± 0.57

CA: chronological age; SA: skeletal age; predicted adult height is based on the TW3 method (Tanner et al., 2001) and was derived from the SonicBone BAUS™ software; z-scores were calculated using predicted adult heights derived from the Khamis-Roche (Khamis & Roche, 1994) method and age-specific means and standard deviations for boys in the Berkeley Growth Study (Bayer & Bailey, 1959).

Participant's standing height, body mass, chronological age at observation and self-reported mid-parental standing height were used to apply the Khamis-Roche method (Khamis & Roche, 1994). The associated mean error ± standard deviation at the 50th percentile of this method was 2.2 ± 0.6 cm between actual and predicted height in young males aged 4 to 18 years (Khamis & Roche, 1994). Standing heights of the biological parents of each participant were self-reported and subsequently adjusted for overestimation using the equations provided by Epstein et al. (Epstein et al., 1995). Although measured parental heights might improve the prediction and strength the concordance between maturity indicators, mean-adjusted paternal and maternal heights (178.8 ± 6.5 cm and 166.9 ± 6.3 cm, respectively) were similar to parent heights in an earlier study (178.2 ± 6.6 cm and 164.9 ± 6.4 cm, respectively) (Malina et al., 2005). These mean parental values fell approximately midway between sex-specific medians and 75th percentiles for United States adults 30-39 years of age (Fryar et al., 2016) and were similar to sex-specific averages for German adults 30-40 years of age (Statistisches Bundesamt (Destatis), n.d.). Biological maturity status was then expressed as a z-score relative to age-specific means and standard deviations for boys in the Berkeley Growth Study (Bayer & Bailey, 1959). Three sets of criteria were applied using the z-score to classify players: i) on time, z-score between -1.00 and +1.00; late, z-score below -1.00; early, z-score greater than +1.00, ii) on time, z-score between -0.75 and +0.75; late, z-score below -0.75; early, z-score greater than +0.75, and iii) on time, z-score between -0.50 and +0.50; late, z-score below -0.50; early, z-score greater than +0.50. Given the variety of previously used criteria, these three cut-offs were used to assess the performance of each criterion in relation to the ±1.0 year band in SA (Hill et al., 2019; Myburgh et al., 2019). Finally, percentage of predicted adult height for each participant was compared to the age- and sex-specific UK 1990 growth data (Cole et al., 1998) to derive an index of maturity status, labelled biological age (BA) to allow for direct comparison of the two maturity estimates (Myburgh et al., 2020).

The BAUS^{TM} system (SonicBone Medical Ltd., Israel) was used to assess skeletal maturity through measuring bone density at three sites of the left hand: wrist (distal radius and ulna's secondary ossification centres of the epiphyses), meta-carpals (distal metacarpal epiphyses), and phalanx (proximal third phalanx shaft of middle finger). SA was automatically determined after each measurement by the manufacturers' proprietary software (BAUS, v 1.0.0.12). Details of this technique have been reported elsewhere (Rachmiel et al., 2017). Briefly, the device measures two parameters: the speed of propagation through bone of high frequency waves of a short ultrasound pulse and the reduction in amplitude of this ultrasound pulse as a function of distance through the bone. Based on these parameters the SonicBone software automatically computes skeletal age based on the TW2 method (formula is protected by a nondisclosure statement) (Tanner et al., 1983). Measurements were performed by the same trained examiner (L.R). Intra-examiner reliability for the three sites was assessed from 39 samples prior to data collection (radius, standardised mean difference (ES): 0.05; coefficients of variation (CV): 0.6%; intra-class correlation coefficient (ICC): 0.97; meta-carpals, ES: 0.02; CV: 0.6%; ICC: 0.97; phalanx, ES: 0.02; CV: 0.3%; ICC: 0.99). A single measurement takes between 4–6 minutes. Predicted adult height (based on the TW2 method (Tanner et al., 1983)) was also derived from the software. The difference between SA and chronological age (CA) was then used to classify players whereby a SA younger than CA by >1.0 years defined late maturity status, a SA within ± 1.0 years of CA defined on-time maturity status and a SA older than CA by >1.0 years defined early maturity status (Malina, 2011). The band of ± 1.0 year approximated standard deviations of SA within single-year CA groups of boys aged 5–17 years in both general and athletic populations (Malina et al., 2018).

4.3.3 Statistical analyses

Normal distribution was verified before statistical analysis using by the Shapiro-Wilks test ($p>0.05$) and visual inspection of Q-Q plots. All data are presented either as mean with standard deviations (SD) or 95% confidence limits (CL). A range of analyses was performed to assess the convergent validity of predicted absolute and percentage adult heights and biological age as derived from the BAUS software and the Khamis-Roche method. First descriptive analyses were conducted to assess the mean, standard deviation, maximum and minimum differences between both methods. Agreement and the presence of a fixed bias between both methods were assessed by calculating Pearson's correlation coefficients (r) and standardised differences or effect sizes (ES, based on Cohen's effect size principle using pooled SD) (Vet et al., 2011). Absolute and relative technical errors of measurement (TEM) as measures of error variability were also calculated to determine the absolute and relative error margin between the two methods (Ulijaszek & Lourie, 1994). Further, cross-tabulations of maturity status classifications based on SA (BAUS™) and z-scores for the percentage of predicted adult height (Khamis-Roche method) were calculated. As in previous studies (Malina et al., 2012; Myburgh et al., 2019), percentage agreement, Cohen's unweighted kappa coefficient (κ), and Spearman rank-order correlations (ρ) were computed to evaluate the concordance of maturity classifications methods. Furthermore, scatterplots and Pearson's correlation coefficients (r) were calculated to evaluate the association between SA-CA differences and z-scores for the percentage of predicted adult height. The following scale was used to interpret κ: ≤0.2 as slight, >0.2-0.4 as fair, >0.4-0.6 as moderate, >0.6-0.8 as substantial, and >0.8-1.0 as almost perfect agreement (Landis & Koch, 1977). Magnitudes for ES values were interpreted as follows: ≤0.2 as trivial, >0.2-0.6 as small, >0.6-1.2 as moderate, and >1.2 as large (Hopkins et al., 2009). The following scale was adopted to interpret the magnitude of r and ρ: ≤0.1 as trivial, >0.1-0.3 as small, >0.3-0.5 as moderate, >0.5-0.7 as large, >0.7-0.9 as very large, and >0.9-1.0 as almost perfect association (Hopkins et al., 2009). All analyses were performed using the RVAideMemoire (version 0.9-73) and stats package (version 3.4.2) with R (version 3.6.2, R Foundation for Statistical Computing, Vienna, Austria).

4.4 Results

Age, standing height, body mass and maturity-related characteristics for each age group are summarised in Table 4.1, while the cross-tabulations of maturity status classifications based SA and percentage of predicted adult height are summarized in Table 4.2. Overall, percentage agreement between classification methods was 68% (95% CL 58 to 76%) for the total sample. The Kappa coefficient κ was 0.37 (95% CL 0.22 to 0.53) for the total sample, indicating fair agreement between both maturity status classifications. Spearman rank-order correlation between maturity classification methods was moderate for the total sample, ρ = 0.48 (95% CL 0.32 to 0.62). Figure 4.1 shows the scatter-plot of the absolute difference between SA minus CA relative to z-scores of the percentage of predicted adult height. It also highlights the respective cut-off points for defining the maturity status for both methods and wrongly classified players. Pearson correlation was 0.66 (95% CL 0.54 to 0.76), indicating a large association between both absolute values. Corresponding analyses for all players categorised in their respective age groups are summarised in the supplementary file (see Appendix B, Chapter 10.2.1, Supplementary Table 10.1, Supplementary Table 10.2, Supplementary Table 10.3, Supplementary Table 10.4, Supplementary Table 10.5, and Supplementary Table 10.6).

Table 4.2. Crosstabulation of maturity status classifications based on z-scores for percentage of predicted adult height and absolute differences between skeletal age (SA) and chronological age (CA) (n = 114).

		Maturity status based on SA-CA difference				**Agreement**		
cut-off z-score	**Maturity status based on percentage of predicted adult height**	**Late**	**On-time**	**Early**	**Total**	**Percent agreement (95% CL)**	**Kappa κ (95% CL)**	**Spearman rank-order correlation (95% CL)**
z = 0.50	Late	2	7	0	9	65%	0.37	0.52
	On-time	3	34	19	48	(55 to 73)	(0.22 to 0.53)	(0.37 to 0.65)
	Early	0	19	38	57			
	Total	5	60	49	114			
z = 0.75	Late	2	2	0	4	68%	0.39	0.49
	On-time	3	53	26	82	(59 to 77)	(0.23 to 0.54)	(0.34 to 0.63)
	Early	0	5	23	28			
	Total	5	60	49	114			
z = 1.00	Late	1	1	0	2	66%	0.31	0.45
	On-time	4	58	33	95	(56 to 74)	(0.17 to 0.45)	(0.32 to 0.57)
	Early	0	1	16	17			
	Total	5	60	49	114			

Agreement between predicted absolute and percentage adult heights as derived from the BAUS system and Khamis-Roche method can be considered acceptable (Table 4.3). Predicted adult heights from the Khamis-Roche method were slightly larger than from the BAUS system, however, Pearson correlation coefficients were very large. Similarly, effect sizes denoting the standardised difference between the predicted adult height from the Khamis-Roche method and the BAUS system were trivial and TEM were fair (Table 4.3). Finally, there was an almost perfect correlation between SA derived from the BAUS system and percentage of predicted adult height derived from the Khamis-Roche method (r = 0.94, 95% CL 0.91 to 0.96) (see Figure 4.3), although magnitudes were slightly worse when analysed by age groups (see supplementary file, Appendix B, Chapter 10.2.1, Supplementary Table 10.7)).

Figure 4.2 illustrates the distributions of z-scores of percentage of predicted adult height (panel A) and absolute differences between SA and CA (panel B) for each age group and the total sample. SA only approximated CA in the U12 and U13 age group with the older age groups demonstrating advanced skeletal maturity status. More specifically, 78% and 65% of U12 and U13 players, respectively, were classified as on-time in maturity status. In contrast, only 42%, 40% and 27% were classified as on-time with the remaining 58%, 60% and 73% being classified as early for the U14, U15 and U16 age groups. A similar pattern was observed for z-scores of percentage of predicted adult height.

Table 4.3. Agreement between the BAUS software and Khamis-Roche method for predicted absolute adult height, percentage adult height and biological age (n = 114).

Variable	**Absolute predicted adult height (cm)**	**Percentage predicted adult height (%)**	**Biological age (years)**
Mean difference ±SD	-0.73 ±3.4	0.37 ±1.8	0.06 ±1.6
Minimum and maximum difference	-8.7; 8.1	-4.8; 4.6	-2.7; 6.2
Pearson correlation coefficient (95% CL)	0.86 (0.81 to 0.90)	0.96 (0.95 to 0.98)	0.80 (0.72 to 0.86)
Effect size (95% CL)	-0.14 (-0.25 to -0.02)	0.06 (0.01 to 0.11)	0.02 (-0.09 to 0.14)
Upper and lower limits of agreement	-7.30 to 5.85	-3.08 to 3.82	-3.10 to 3.22
Absolute and relative (%) technical error of measurement	2.4; 1.3%	1.3; 1.4%	1.1; 1.2%

4.5 Discussion

The aim of the present study was to assess the construct validity of the BAUS^{TM} system and percentage of predicted adult height based on the Khamis-Roche method to assess biological maturity status in a German professional soccer academy. Our findings show that SA as derived from the BAUS^{TM} system and percentage of predicted adult height were almost perfectly interrelated. In contrast, concordance of maturity status classifications was relatively poor to moderate between both methods confirming our initial hypotheses. In partial support of our second aim, there was a selection bias towards players advanced in biological maturation emerging in the U14 age group which remained relatively consistent through to the U17 age group. Taken together, these findings demonstrate that both methods are able to quantify the construct of biological maturity status. However, caution is warranted when comparing the classification of athletes as early, on-time or late maturing from different maturity status classification methods given the poor concordance between methods due to the associated limitations of arbitrarily dichotomising continuous variables. It is therefore recommended to use pre-defined cut-off values as a guide and interpret differences in maturity status in conjunction with the measurement error of the respective system.

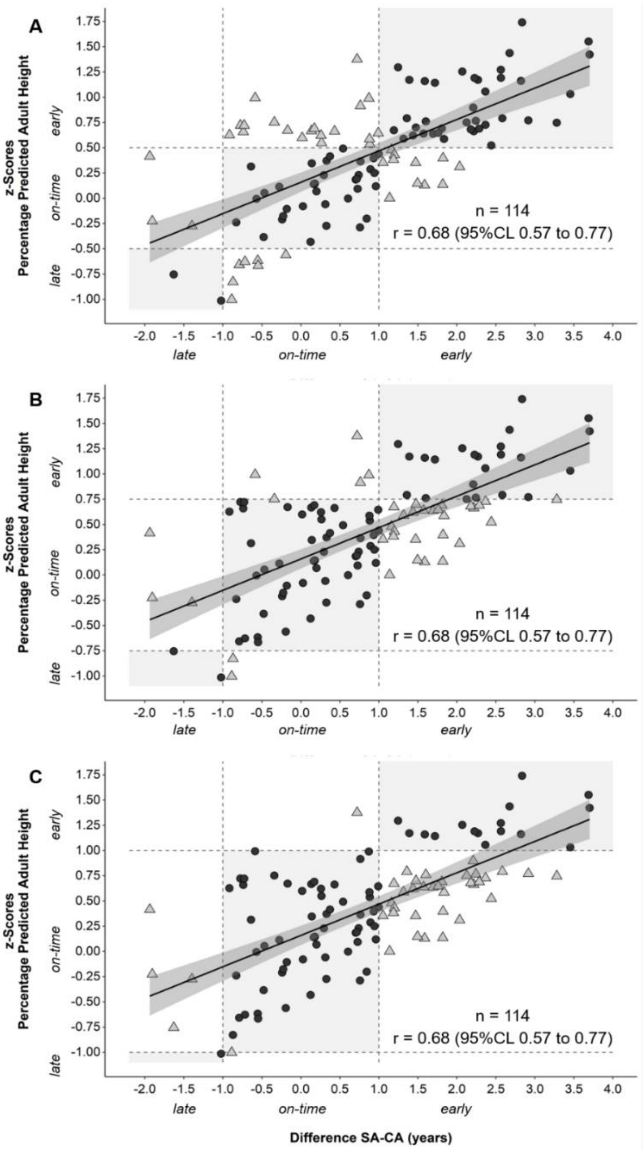

Figure 4.1. Scatterplot on the absolute difference between skeletal age (SA) and chronological age (CA) and z-scores for the percentage of predicted adult height. Three sets of criteria were applied using the z-score to classify early, on-time and late maturity status: z-score = ±0.50 (upper panel, A), z-score = ±0.75 (middle panel, B), z-score = ±1.00 (lower panel, c). Note that black circles indicate the same maturity classification with each method, while grey triangles indicate disagreement between maturity classification methods.

Results of the convergent validity analysis using SA derived from the ultrasound based BAUS^{TM} system and percentage of predicted adult height derived from the Khamis-Roche method were generally comparable with studies in community-level American football (Malina, Dompier, et al., 2007), club-level soccer (Malina et al., 2012) and elite tennis (Hill et al., 2019) investigating the interrelationships between skeletal and somatic maturity using standard radiographs. Maturity status classifications based on percentage of predicted adult height had moderate concordance with classifications based on SA (Fels method) in these studies with kappa coefficients ranging from 0.22 to 0.46. Kappa coefficients of our sample were of similar magnitude and (κ=0.31 to 0.39) but varied with age (see supplementary file). This variability is likely due to the differential tempo of maturation of different biological systems (Ratel & Williams, 2017) and the application one uniform cut-off threshold across all age groups to classify players as early, on-time and late maturing (see below). Overall agreement between classifications ranged between 57% to 70% and spearman rank-order correlations were moderate (ρ=0.45 to 0.52). These data are again consistent with the reported data (agreement: 57 to 70%, ρ=0.27 to 0.47) from the previously mentioned studies (Malina, Dompier, et al., 2007; Malina et al., 2012; Myburgh et al., 2019). Moreover, large agreements and small systematic errors were observed between the BAUS software and Khamis-Roche method for predicted absolute adult height, percentage adult height and biological age (Table 4.3). Corresponding data in athletic populations are lacking. While the values produced by the BAUS^{TM} system and Khamis-Roche method assess different aspects of maturation (skeletal vs. somatic) and classifications were not expected to correspond exactly, the level of agreement between these methods for assessing the construct maturity status was acceptable. Moreover, SA derived with each assessment protocol (i.e. Greulich-Pyle, Fels, TW2, TW3), though related, are not equivalent as criteria, methods and references differ among methods (Malina et al., 2018). It is unclear how these factors influenced SA assigned by the BAUS^{TM} system and in turn the convergent validity. Therefore, further evaluation against other maturity estimates (i.e., Greulich-Pyle, Fels, TW2, TW3) in healthy youth are needed.

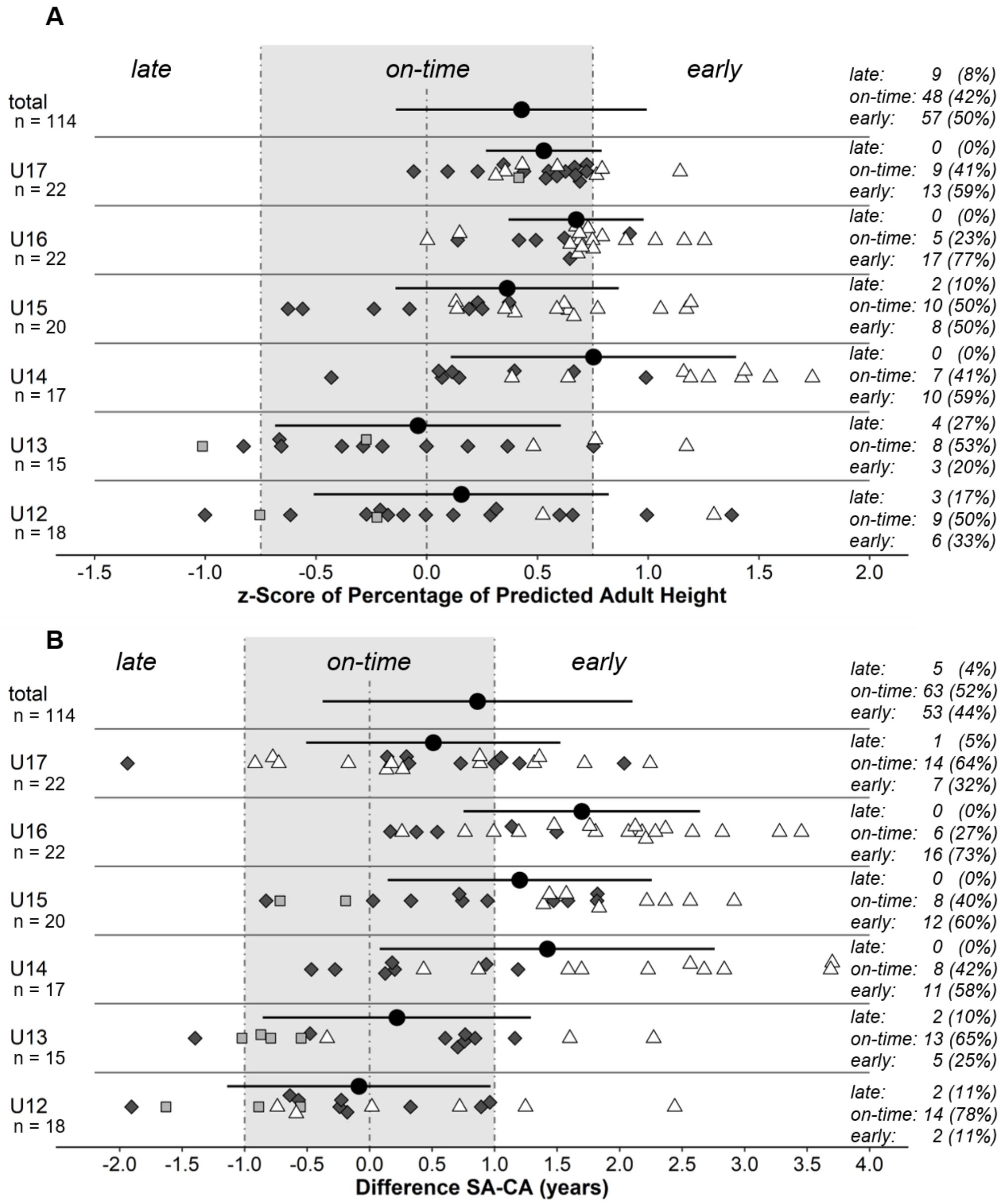

Figure 4.2. Z-scores of percentage of predicted adult height (upper panel, A) and absolute differences between skeletal age (SA) and chronological age (CA) (lower panel, B) for the total sample and all age groups. Black circles denote age group averages ±SD. For panel A, grey squares (■) denote late, grey diamonds (◆) denote on-time, and white triangles (△) denote early maturing players within each age group with respect to the maturity status classification based on the BAUS system and vice versa for panel B.

Little attention has been given to the commonly used maturity classification criteria for late, on-time and early maturing players. Although the band of ±1.0 year is widely adopted in studies of youth athletes as this approximates standard deviations for SA within single CA groups during adolescence in general populations of youth and to accommodate error associated with skeletal maturity assessments, it somewhat varies with CA (Malina et al., 2018) whereby variation is greatest at the on-set of puberty and then steadily decreases (e.g. U14: ± 1.4 vs. U17: ± 0.9). This highlights the difficulty in applying one uniform cut-off value to adolescent athletes of varying CA and maturity status. A similar trend has been noted for z-score of predicted adult height (e.g. U14: ± 0.7 vs. U17: ± 0.3), likely affecting the sensitivity of the maturity classifications to each category (Hill et al., 2019). Therefore, three different z-score cut-off criteria have been used in this study to assess the performance of each criterion in relation to the ±1.0 year band in SA. Of note, predicted adult height was based on equations for youth in southwest Ohio (Fels study (Roche, 2008)), while z-scores were calculated based on percentages of predicted adult height attained at different chronological ages by a relatively small sample of boys in the Berkeley study (Bayley & Pinneau, 1952). While only small differences were evident between the three cut-off criteria when analysing the entire sample, it should be noted that concordance varied substantially with age group and among cut-off criteria. More specifically, the z=0.75 cut-off performed best for the U12 and U17 age groups while the z=1.00 criteria was slightly superior for the U13 and U14 age groups and the z=0.50 cut-off was most sensitive for the U15 and U16 age groups (see supplementary file). Collectively, this highlights the need to refine cut-off criteria for classification methods as arbitrarily dichotomising continuous variables impacts the sensitivity of concordance analysis (Altman & Royston, 2006).

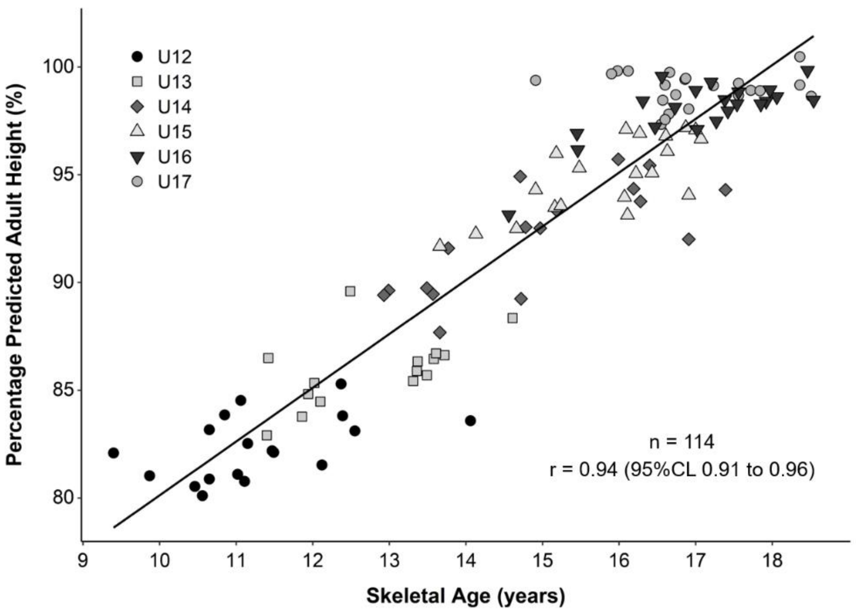

Figure 4.3. Scatterplot on skeletal age derived from the BAUS system and percentage of predicted adult height derived from the Khamis-Roche method. Note that shaded shapes indicate different age groups.

Similar to previous research, this sample of elite youth soccer players was, on average, advanced in SA relative to CA (+0.9 ±1.2 years) and z-scores of percentage of predicted adult height (+0.43 ± 0.57, Table 4.1). Late-, on-time-, and early-maturing players were equally represented within the U12 and U13 age group, however, a selection bias emerged in the U14 age group and remained relatively consistent through to the U17 age group favouring early- and on-time maturing players while players late in SA were underrepresented with only one player being represented in the U17 age group. These data are consistent with previous observations of male youth players aged 11 to 17 years (Hirose, 2009; Johnson et al., 2017; Malina, Chamorro, et al., 2007), although differences in SA between assessment protocols (i.e. Tanner-Whitehouse, Greulich and Pyle, and Fels method) need to be acknowledged (Malina et al., 2015). More careful observation of Figure 4.2b highlights also the large inter-individual variation in skeletal maturity within age groups with observed absolute differences of up to 4.5 years. Similar large variation in SA among players of the similar CA have been previously reported in youth soccer players (Malina, 2011). This demonstrates the known-group validity of the percentage of predicted adult height method and BAUS™ system whereby both measures were able to discriminate between athletes of different maturity status that are expected to differ based on the well-established evidence on maturity-related selection bias in elite youth soccer academies (Hill et al., 2019; Johnson et al., 2017; Malina et al., 2010).

4.6 Limitations

Several limitations of the current study must be acknowledged. First, potential bias of self-reported standing heights (average bias: 1.4 cm in men, 0.7 cm in women (Roberts, 1995)) of biological parents should be noted, although parental heights were adjusted for overestimation. The lack of a clinical established indicator of SA (i.e., hand-wrist radiograph) prevents us from drawing firm conclusions regarding the criterion validity of the BAUS™ system. However, given the associated expenses, logistical constraints and the lack of qualified individuals knowledgeable of the different assessment protocols and interpretations in the sport sciences associated with standard radiographs, the current study design aimed to compare the BAUS™ system against practically used methods such as the percentage of predicted adult height as an established non-invasive indicator of maturity status.

4.7 Conclusion

Results of the present study suggest that both indicators considered were largely interrelated, however, agreement between maturity classifications methods were moderate at best. Results also highlight the apparent selection bias towards players who advanced in biological maturity in a professional youth soccer academy, irrespective of the method used. Taken together this demonstrates the construct validity of the BAUS™ system and percentage of predicted adult height to assess biological maturity status in healthy youth soccer players. However, there is a need for further refinement and validation of both investigated protocols (i.e., skeletal age derived from the BAUS™ system and percentage of predicted adult height derived from the Khamis-Roche method) relative to established indicators of biological maturity in youth.

Chapter 5: Poor reliability of measurement instruments to assess acute responses to load in soccer players irrespective of biological maturity status.

This study has been accepted for publication following peer review in the journal *Pediatric Exercise Science*. The content has been reformatted for the purposes of this thesis. The full reference details of this published study are:

Poor reliability of measurement instruments to assess acute responses to load in soccer players irrespective of biological maturity status.

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5.1 Abstract

Purpose: To assess the short-term reliability of measurement instruments to quantify the acute psycho-physiological response to load in adolescent soccer players in relation to biological maturity.

Methods: Data were collected from 108 U12 to U17 soccer players on two consecutive weeks (pre- (n=32), at- (n=34) and post- (n=42) estimated peak height velocity). Measurements consisted of the Short Recovery and Stress Scale (SRSS), a countermovement jump (CMJ), assessment of leg stiffness and a sub-maximal run to assess exercise heart-rate (HRex) and heart-rate recovery (HRR60s). Test-retest reliability was assessed with the coefficient of variation (CV) and intra-class correlation coefficient (ICC).

Results: Items of the SRSS showed poor reliability across maturity groups (CV: 7.0 to 53.5%; ICC: 0.28 to 0.79). Only few CMJ variables (jump height, concentric impulse, and concentric velocity) possessed good reliability. For most variables of the CMJ, reliability was better for the post-PHV group followed by at-PHV and pre-PHV. Very high levels of reliability across maturity groups were observed for HRex (CV: <1.8%; ICC: >0.94), while HRR60s was more variable (CV: <16.5%; ICC: >0.48).

Conclusion: Results suggest that the majority of investigated variables have poor reliability questioning their ability to detect small, yet meaningful changes in acute responses to load in adolescent soccer players.

Keywords: maturation, fatigue, monitoring, smallest detectable change, adolescence

5.2 Introduction

Developing youth athletes is a complex and dynamic process which requires the integration of a multitude of activities to foster their development across years. This process also encompasses balancing the accumulation of training load and subsequent acute and chronic responses. Athlete monitoring systems are therefore routinely used in professional soccer to provide coaches and practitioners with information about training load exposure and psycho-physiological response pattern to load (Sands et al., 2017). In this context, monitoring the acute response can be understood as quantifying the changes in psychological and physiological systems of up to 72 h post-exercise. Importantly, an athlete's psycho-physiological response can be conceptualised as existing on a continuum ranging from a transient state of maximal disturbance to functional adaptation of the respective system. Such information is then used to guide the training process by manipulating training volume and intensity to optimise the functional adaptive response whilst guarding against maladaptive training outcomes such as non-functional overreaching (Impellizzeri et al., 2019). However, the complex interaction between several physiological and psychological mechanisms requires multiple measurement instruments from different domains to holistically capture the multitude of psycho-physiological systems. These domains typically range from the cellular level (e.g. creatine kinase (CK)) to athlete-reported symptoms (e.g. stress and recovery), submaximal heart rate tests, and functional performance tests (e.g. countermovement jump (CMJ) (Akenhead & Nassis, 2016).

Recent advancements in technology have increased the availability of measurement instruments to assess the constructs of training load and acute psycho-physiological responses to load. In the context of athletic training, training load as a generic construct reflects the input variable that accommodates a variety of measures of various nature (spatio-temporal, mechanical, psycho-physiological etc.) which can be described as being either external or internal (Impellizzeri et al., 2005). While external load refers to the prescribed organisation, quality and quantity of the training plan, internal load reflects the actual psycho-physiological responses during the execution of exercise (Impellizzeri et al., 2019). The subsequent response of a given psycho-physiological system then follows a unique pattern characterised by a transient fatigue and adaptation response trajectory (Sands et al., 2017). Depending on the magnitude of the internal load of an athlete the response pattern of each psycho-physiological system can vary from a few minutes to 72 hours after a bout of physical activity (Silva et al., 2018) indicating distinct recovery profiles. Quantifying the magnitude of the acute response to load has therefore important implications for optimally prescribing the appropriate external load for the next training session. To do so, reliable measurement instruments are needed allowing practitioners to accurately assess psycho-physiological response pattern within the constraints of a high-level sports environment (e.g., time restrictions, access to athletes, focus on competitions).

Youth athletes experience rapid changes in growth and biological maturity throughout adolescence. This time period is also associated with maturation related non-linear psychological, neuromuscular and physiological changes. Recent evidence has suggested that biological maturity plays an important role in the development of the adolescent brain, due to the substantial changes in hormone levels (Blakemore et al., 2010). Specifically, maturity status has been shown to be related to grey and white matter development during adolescence affecting various behavioural and psychological aspects (Goddings, 2015). For example, during adolescence the emphasis shifts from a spontaneous emotional response to a more logical response. Additionally, less mature athletes might not cope as effectively with acute and chronic stress compared to more mature athletes (Romeo, 2013) potentially influencing the reliability of athlete-reported symptoms such as stress and recovery in relation to biological maturity. Additionally, substantial neuromuscular and physiological changes occur during adolescence as a result of maturation (Beunen & Malina, 1988). In particular, increases in muscle cross-sectional area, pre-activation, tendon stiffness, and decreases in agonist-antagonist co-contraction result in an improved stretch-shortening cycle function (Radnor et al., 2018). Importantly, these changes do follow a non-linear maturity-related pattern. Less mature athletes possess a more reactive and less efficient movement evolving to a more pre-active controlled movement as they mature. As commonly used measurement instruments such as CMJ, sub-maximal hopping and running rely upon the adaptations underpinned by the stretch-shortening cycle, reliability of these tasks might be impacted by biological maturation status.

Reliability is an essential aspect in the evaluation of the measurement properties. Reliability refers to the degree to which the measurement is free from measurement error (Vet et al., 2011). To establish reference values for measurement instruments that are beyond measurement error the smallest detectable change (SDC) can be calculated. To do so, assessments are repeated on different occasions under similar conditions (i.e., test-retest reliability). Importantly, these reference values are specific to the population under investigation as the variance between subjects differs between populations which in turn determines the magnitude of the test-retest reliability (Streiner et al., 2015). Therefore, it is pivotal that such information is available to researchers conducting research or practitioners working with adolescent youth soccer players. Currently, there is an absence of reliability data within the population of youth soccer players of different maturity status. A high test-retest reliability is pivotal to detect small yet potentially meaningful changes within athletes over time (Buchheit, 2014). Whether a measurement instrument that has shown to be reliable with senior professional athletes is reliable with developing athletes of different maturity status is an empirical issue that warrants formal investigation.

Therefore, the aim of this study was to assess the short-term between-day reliability of commonly used measurement instruments to quantify the acute psycho-physiological response to load in youth soccer players in relation to biological maturity status. Since changes in physiological and physical characteristics are associated with the natural changes occurring as a consequence of growth and biological maturity (Beunen & Malina, 1988), we expected to observe better reliability as players mature.

5.3 Methods

5.3.1 Participants

A total of 108 male youth soccer players (age: 14.0±1.7 years, standing height: 165.3±12.5 cm, body mass: 54.3±13.0 kg, percentage predicted adult height: 91.9±6.2%) agreed to participate in this study. Participants were selected from the U12 to U17 age groups: U12 (n=16), U13 (n=15), U14 (n=19), U15 (n=31), U16 (n=14), and U17 (n=13) as these age groups included players from different stages of biological maturity (i.e., pre-pubescent; pubescent, post-pubescent). Participant characteristics in relation to biological maturity are presented in Table 5.1. All participants were medically cleared to participate in formalised soccer practice. Prior to the commencement of the study, all participants were informed about the aims, procedures and risks of the investigation. Parental or guardian consent for all participants involved in this study was obtained. The study was approved by the institutional ethics committee of Saarland University and was conducted according to the Declaration of Helsinki.

Table 5.1. Anthropometric characteristics in relation to biological maturity status.

Variables	**Pre-PHV (n=32)**	**At-PHV (n=34)**	**Post-PHV (n=42)**
Age (years)	11.9±0.7	13.9±0.8	15.6±0.9
Standing height (cm)	151.6±6.4	165.1±8.1	176.0±7.8
Body mass (kg)	41.2±6.2	52.4±7.6	65.8±9.5
Percentage predicted adult height (%)	83.8±2.7	92.1±1.6	98.1±1.4

Notes: PHV=peak height velocity

5.3.2 Study design

A repeated-measures design was used to allow for the assessment of test-retest reliability of commonly used measurement instruments aimed to infer upon acute psycho-physiological responses to load in elite youth soccer players. This study was completed during the 2019-20 and 2020-21 season and consisted of one familiarisation and two testing blocks separated by seven days. Each testing session was conducted on the same time of day (16:30 to 18:30) to minimise the impact of circadian rhythm on athletic performance. The familiarisation block comprised the same structure as the testing block to fully familiarise participants with the testing equipment and procedure. Within each block, an assessment battery was conducted after 48 h of rest and immediately prior to the regular training session. Measurements consisted of a subjective recovery-stress status questionnaire (Short Recovery and Stress Scale, SRSS), a countermovement jump (CMJ) on a force plate, assessment of leg stiffness on a contact mat and a sub-maximal run (exercise heart rate, HRex; heart rate recovery, HRR60s).

5.3.3 Procedures

5.3.3.1 Anthropometry and maturation status

Participant's standing height, body mass, chronological age at observation and mid-parent standing height were used to predict adult height of each participant (Khamis & Roche, 1994). Applying this method, the mean error ± standard deviation at the 50th percentile was 2.2 ± 0.6 cm between actual and predicted height in young males between 4 and 18 years of age (Khamis & Roche, 1994). Standing heights of the biological parents of each participant were self-reported and subsequently adjusted for overestimation using the equations provided by Epstein et al. (Epstein et al., 1995). The current standing height of each participant was then expressed as percentage of the predicted adult height (PPAH) to provide an estimation of somatic maturation status (Khamis & Roche, 1994). For analysis, participants were then allocated into three bands, pre-PHV (<89%), at-PHV (89-95%), and post-PHV (95-100%) reflecting the somatic developmental stages of adolescence (Molinari et al., 2013). Standing height (± 0.1 cm, seca 213 portable stadiometer, Seca, Hamburg, Germany) and body mass (± 0.1 kg, seca 813, calibrated digital scale, Seca, Hamburg, Germany) were measured according to standardised ISAK measurement techniques one week prior to the first testing session at the same time of the day.

5.3.3.2 Short Recovery-Stress Scale

On testing days, participants completed the German version of the Short Recovery and Stress Scale (SRSS, (Kellmann et al., 2016), English version (Nässi et al., 2017)) upon arriving at the training facilities. The questionnaire consisted of two constructs, recovery and stress. Each construct contained four items addressing the physical, mental, emotional, and overall status. Each item was scored on a seven-point Likert scale with single point increments, ranging from does not apply at all (0) to fully applies (6). Structural, construct and cross-cultural validity and strong internal consistency have been reported for both the recovery-related (α=0.74 to 0.82) and stress-related items (α=0.78 to 0.81) (Nässi et al., 2017; Pelka et al., 2018).

5.3.3.3 Countermovement jump and sub-maximal hopping test

Following a standardised dynamic warm-up consisting of dynamic stretching and sub-maximal jumping, participants performed three CMJs and three sub-maximal two-legged hopping tests (SHT) to calculate leg stiffness. In both the CMJ and SHT, participants were required to keep their hands held in place on the hips. For the CMJ, participants were instructed to jump as high as possible, while for the SHT participants were also required to minimise ground contact time between jumps. CMJ depth and stance were self-selected by the participant to maximise the potential application to practical settings. As for the CMJ, jumps were performed on a portable force plate sampling at 500 Hz (Kistler Quattro Jump, Type 9290DD, Kistler Instruments, Sindelfingen, Germany). Unfiltered force-time data were processed and analysed using a customizable Microsoft Excel spreadsheet (Chavda et al., 2018) following the methods previously described by Lake et al. (Lake et al., 2018). Table 5.2 describes all variables derived from the force-time data of the CMJ. Similar to previous research CMJ variables referring to the outcome (i.e. performance such as jump height) and strategy (i.e. phase-specific variables preceding the outcome) were selected (Gathercole et al., 2015). As for the SHT, participants performed 20 consecutive hops for each trial on a contact mat (Haynl-Elektronik, Schönebeck, Germany) at a frequency of 2.5 Hz. After discarding the first and last five hops, the remaining ten hops were averaged to calculate absolute ($kN.m^{-1}$) leg stiffness using equation 2 provided by Delleau et al. (Dalleau et al., 2004):

Absolute leg stiffness = $[M*\pi(T_f+T_c)]/T_c^2[(T_f+T_c/\pi)-(T_c/4)]$, whereby M refers to the body mass of the athlete, T_c represents the ground contact time and T_f is the flight time.

Subsequently, absolute leg stiffness was divided by body mass to derive relative leg stiffness (Ste Croix et al., 2017).

Relative leg stiffness = absolute leg stiffness/M, whereby M refers to the body mass of the athlete.

To improve the precision in each of the daily measurement, the average of the 3 CMJs normalised by body mass and sub-maximal hopping test was utilised for analysis (Taylor et al., 2010).

5.3.3.4 Sub-maximal run

A 4-min continuous shuttle run followed by a 1-min passive (standing) recovery period was performed outdoor at the start of the training session on an artificial turf. All players were tested at the same time with the intensity of the run being individualised for every age group. Specifically, shuttle distances, times and corresponding average speeds were as follows: 45 m in 15 s (10.8 $km.h^{-1}$) for U12 to U14, and 50 m in 15 s (12.0 $km.h^{-1}$) for U15 to U17. These formats were chosen based on pilot testing which elicited heart rate responses of 85% to 90% of maximal heart rate and previous research that found that higher relative heart rate responses (i.e. >85% of maximal heart rate) improved reliability in heart rate responses during and post-exercise (Lamberts & Lambert, 2009). After the 4-min continuous shuttle run players were required to remain in a stationary standing position avoiding any movement. Heart rate was recorded continuously at 1 Hz (Polar H3 Sensors; Polar Electro Oy, Kempele, Finland) and raw data were subsequently downloaded from manufacturers' proprietary software (Polar ProTrainer 5™, version 5.40.170, Polar Electro Oy, Kempele, Finland). Mean heart rate during the final 30 seconds (HRex, $beats.min^{-1}$) of the 4-min continuous shuttle run was computed (Rabbani et al., 2018; Veugelers et al., 2016). Heart rate recovery was calculated as the absolute difference between HR_{ex} and heart rate after the 1-min recovery period (HRR60s, beats.min^{-1}).

Table 5.2. Description of all computed counter-movement jump (CMJ) variables

CMJ Variable	Unit	Abbreviation	Description
Jump height	cm	JH	The maximum jump height achieved based on vertical take-off velocity: take-off velocity^2 ÷ 2g.
Reactive strength index modified	m.s^{-1}	RSImod	Ratio between jump height and total time to take-off.
Eccentric Rate of Force Development	N.s^{-1}	RFD	Largest force increase during a 30 ms epoch.
Eccentric Impulse	N.s	EccI	Force exerted during eccentric phase multiplied by the time of the eccentric phase.
Concentric Impulse	N.s	ConI	Force exerted during concentric phase multiplied by the time of the concentric phase.
Eccentric Velocity	m.s^{-1}	EccV	Mean velocity achieved during the eccentric CMJ phase.
Concentric Velocity	m.s^{-1}	ConV	Mean velocity achieved during the concentric CMJ phase.
Force at Zero Velocity	N	F@0V	Force when velocity is zero (transition from eccentric to concentric).
Duration of Eccentric Phase	ms	DurEcc	Time required to perform the eccentric CMJ phase.
Duration of Concentric Phase	ms	DurCon	Time required to perform the concentric CMJ phase.
Countermovement Depth	cm	CMD	The minimum (i.e. peak negative) displacement when velocity is zero (transition from eccentric to concentric).

5.3.4 Statistical analyses

Data are presented either as mean with standard deviations (SD) or 90% confidence limits. Between-days reliability was assessed by calculating the typical error of measurement (TE, standard deviation of the difference scores divided by √2, absolute reliability), the coefficient of variation (CV, absolute reliability) (Bland & Altman, 1996), and intra-class correlation coefficient (relative reliability, two-way fixed effects ICC (3,1)). The magnitude of the systematic bias was assessed by calculating standardized differences or effect sizes (ES, based on Cohen's d's effect size principle using pooled SD). Finally, the smallest detectable change (SDC), defined as the smallest change in the measurement instrument that is beyond measurement error, was calculated at 90% confidence level using the formula $SDC_{90} = 1.645 \times \sqrt{2} \times SEM$ (Vet et al., 2011). Nonparametric bootstrapping (resamples: 10000, type: bias corrected and accelerated) was used to derive confidence limits using the boot package (Canty & Ripley, 2020) in Rstudio (version 1.2.5033, RStudio Inc.). No threshold for the CV was defined a priori to determine the acceptance of acceptable reliability as the magnitude of the measurement error needs to be interpreted in relation to the usually observed changes and the minimal important changes (Buchheit, 2014). Threshold values for ES statistics were as follows: ≤0.2 (trivial), >0.2-0.6 (small), >0.6-1.2 (moderate), and >1.2 (large) (Hopkins et al., 2009). ICC was interpreted using the following thresholds: ≤0.50, poor; >0.50-0.75, moderate; >0.75-0.90, good; >0.90-1.00, excellent (Koo & Li, 2016).

5.4 Results

Descriptive statistics for each variable and associated reliability measure for pre-PHV, at-PHV and post-PHV are displayed in Table 5.3, Table 5.4, and Table 5.5, respectively. Standardised differences between trials were mostly trivial (ES < 0.2) to small, indicating no systematic bias for any variable, irrespective of the maturity status (see Appendix B, Chapter 10.2.2, Supplementary Table 10.8, Supplementary Table 10.9, and Supplementary Table 10.10).

Between-days reliability for the recovery construct of the SRSS questionnaire was more reliable in pre-PHV (CV: 8.7 to 38%; ICC: 0.28 to 0.59) and at-PHV (CV: 7.0 to 46.8%; ICC: 0.56 to 0.79) compared with post-PHV (CV: 17.8 to 51.0%; ICC: 0.32 to 0.62). Similar values of ICC ranging from poor to moderate (0.36 to 0.74), but larger CVs (30.8 to 53.5%) across trials were evident for the stress construct of the SRSS questionnaire, irrespective of the maturity status. SDC's ranged from 1.1 to 1.5 across items.

Variables of the CMJ that showed high levels of reliability were jump height, concentric impulse, and concentric velocity (CV < 5.8%; ICC > 0.71). RSImod, countermovement displacement and leg stiffness also displayed good overall reliability (CV < 13.0%; ICC > 0.74). Eccentric rate of force development was the least reliable variable overall across all maturity groups (CV: 20.4 to 28.5%; ICC: 0.71 to 0.90). For most variables, reliability was better for the post-PHV group followed by at-PHV and pre-PHV groups.

High levels of reliability were evident across all maturity groups for HRex (CV: 1.5 to 1.8%; ICC: 0.90 to 0.94) although greater variability was observed for HRR60s (CV: 12.8 to 16.5%; ICC: 0.48 to 0.71). For HRex a change of around 7 bpm is needed to exceed measurement error irrespective of maturity group, while for HRR60s a change of at least 13, 17 and 19 bpm is needed for the pre-, at- and post-PHV group, respectively.

Table 5.3. Reliability statistics for the Short Recovery and Stress Scale (SRSS) for the pre-PHV, at-PHV, and post-PHV maturity group.

Variable	**Trial 1 (±SD)**	**Trial 2 (±SD)**	**Mean change (±SD)**	**TE (90%CL)**	**CV (90%CL)**	**ICC (90%CL)**	**SDC (90%CL)**
Pre-PHV maturity group, n=32							
Physical recovery	6.4±0.7	6.7±0.6	0.3±0.7 small	0.5 (0.4; 0.7)	8.7 (6.8; 11.3)	0.51 (0.17; 0.76)	1.1 (0.8; 1.6)
Mental recovery	6.5±0.7	6.5±0.8	0.0±0.8 trivial	0.6 (0.4; 0.8)	10.1 (6.5; 16.9)	0.44 (0.06; 0.72)	1.3 (0.9; 2.0)
Emotional recovery	6.3±0.8	6.5±0.8	0.2±0.9 small	0.7 (0.5; 0.8)	11.8 (9.4; 14.7)	0.28 (-0.04; 0.56)	1.5 (1.3; 1.9)
Overall recovery	6.3±0.9	6.4±0.7	0.2±0.8 trivial	0.6 (0.4; 0.9)	11.0 (7.6; 17.6)	0.39 (0.05; 0.66)	1.4 (1.0; 2.0)
Physical stress	2.0±1.1	1.7±0.7	-0.3±0.8 small	0.6 (0.5; 0.7)	34.6 (25.3; 46.8)	0.59 (0.37; 0.74)	1.4 (1.1; 1.6)
Mental stress	1.4±0.9	1.3±0.6	-0.1±0.8 trivial	0.6 (0.4; 0.8)	36.3 (25.9; 49.9)	0.43 (0.03; 0.68)	1.4 (1.0; 1.8)
Emotional stress	1.5±0.7	1.4±0.9	-0.1±0.9 trivial	0.6 (0.4; 0.9)	36.6 (27.3; 46.6)	0.46 (0.24; 0.71)	1.4 (1.0; 2.1)
Overall stress	1.6±1.0	1.3±0.7	-0.3±0.9 small	0.6 (0.4; 1.0)	38.0 (26.7; 60.3)	0.49 (0.04; 0.85)	1.5 (0.9; 2.4)
At-PHV maturity group, n=34							
Physical recovery	6.2±0.9	6.1±0.9	-0.1±0.6 trivial	0.4 (0.3; 0.6)	7.0 (5.0; 10.0)	0.79 (0.57; 0.90)	0.9 (0.7; 1.3)
Mental recovery	6.2±0.9	5.9±1.0	-0.2±0.7 small	0.5 (0.4; 0.6)	9.7 (7.3; 13.3)	0.74 (0.56; 0.86)	1.1 (0.9; 1.5)
Emotional recovery	6.1±0.9	6.0±0.9	-0.1±0.6 trivial	0.4 (0.3; 0.6)	7.8 (5.7; 10.6)	0.76 (0.52; 0.87)	1.0 (0.7; 1.4)
Overall recovery	5.5±1.2	5.6±1.3	0.1±1.1 trivial	0.8 (0.6; 1.2)	17.5 (12.2; 27.1)	0.56 (0.14; 0.79)	1.9 (1.4; 2.7)
Physical stress	2.4±1.4	2.2±1.4	-0.1±1.3 trivial	0.9 (0.6; 1.4)	46.8 (31.5; 73.2)	0.57 (0.15; 0.83)	2.1 (1.4; 3.3)
Mental stress	1.9±1.2	1.9±1.2	0.0±0.8 trivial	0.6 (0.3; 1.0)	30.8 (18.6; 54.4)	0.74 (0.31; 0.93)	1.4 (0.7; 2.4)
Emotional stress	1.8±1.1	1.6±0.8	-0.2±0.9 trivial	0.6 (0.5; 0.9)	38.2 (28.9; 49.7)	0.58 (0.33; 0.78)	1.5 (1.1; 2.0)
Overall stress	2.1±1.2	2.1±1.2	0.0±1.1 trivial	0.8 (0.6; 1.1)	39.9 (31.9; 49.4)	0.57 (0.39; 0.73)	1.9 (1.5; 2.5)
Post-PHV maturity group, n=42							
Physical recovery	5.6±1.2	5.4±1.0	-0.2±1.3 trivial	0.9 (0.8; 1.1)	20.8 (16.8; 26.5)	0.36 (0.10; 0.59)	2.1 (1.7; 2.5)
Mental recovery	5.8±1.1	5.8±0.9	0.0±1.2 trivial	0.9 (0.7; 1.0)	17.8 (14.6; 22.9)	0.32 (0.10; 0.60)	2.0 (1.7; 2.4)
Emotional recovery	5.7±1.3	5.8±1.2	0.1±1.4 trivial	1.0 (0.9; 1.2)	24.7 (19.0; 35.3)	0.36 (0.08; 0.61)	2.3 (2.0; 2.8)
Overall recovery	5.4±1.3	5.3±1.3	0.0±1.4 trivial	1.0 (0.8; 1.3)	24.3 (19.2; 31.3)	0.39 (0.11; 0.59)	2.3 (2.0; 2.9)
Physical stress	2.8±1.5	2.7±1.2	0.0±1.5 trivial	1.1 (0.9; 1.3)	52.1 (42.7; 66.4)	0.34 (0.10; 0.51)	2.5 (2.2; 3.1)
Mental stress	2.0±1.2	2.0±1.1	0.0±1.1 trivial	0.8 (0.6; 1.0)	47.5 (37.8; 60.2)	0.57 (0.32; 0.74)	1.8 (1.5; 2.3)
Emotional	2.1±1.4	2.2±1.4	0.1±1.2	0.9	44.7	0.62	2.0

stress			trivial	(0.7; 1.1)	(35.2; 57.1)	(0.35; 0.82)	(1.6; 2.7)
Overall	2.2±1.1	2.5±1.3	0.3±1.4	1.0	51.0	0.36	2.3
stress			small	(0.9; 1.2)	(42.6; 61.9)	(0.16; 0.54)	(2.0; 2.8)

Notes: TE=typical error; CV=coefficient of variation; ICC=intra-class correlation coefficient; SDC=smallest important change at 90% confidence level; mean change is supplemented with qualitative description of standardized differences, exact standardized mean differences can be found in the supplementary file

5.5 Discussion

The aim of the current investigation was to determine the short-term between-day reliability of commonly used measurement instruments to quantify the acute psycho-physiological response to load in relation to biological maturation in male youth soccer players. The results of the study demonstrated that 1) single-items for the constructs recovery and stress of the SRSS showed poor reliability 2) only few variables of the CMJ and submaximal run possessed good reliability across all three maturity groups, and 3) there was a maturity-related gradient, whereby better reliability statistics were observed in the post-PHV followed by at-PHV and pre-PHV cohort for the CMJ and sub-maximal hopping test, while all items of the SRSS were the least reliable for the post-PHV cohort. Collectively, these findings highlight a relatively poor short-term between-day reliability of most measurement instruments irrespective of the maturity status questioning their ability to detect small, yet meaningful changes in psycho-physiological responses to load in youth soccer.

Table 5.4. Reliability statistics for the countermovement jump and leg stiffness for the pre-PHV, at-PHV, and post-PHV maturity group.

Variable	**Trial 1 (±SD)**	**Trial 2 (±SD)**	**Mean change (±SD)**	**TE (90%CL)**	**CV (90%CL)**	**ICC (90%CL)**	**SDC (90%CL)**
Pre-PHV maturity group, n=31							
JH	24.3±3.8	23.8±4.4	-0.5±1.6	1.1	4.7	0.92	2.6
			trivial	(1.0; 1.4)	(4.1; 5.4)	(0.88; 0.95)	(2.2; 3.2)
RSImod	0.24±0.07	0.26±0.08	0.01±0.04	0.03	13.0	0.85	0.07
			trivial	(0.02; 0.04)	(10.3; 16.8)	(0.68; 0.93)	(0.06; 0.09)
RFD	84.9±40.9	95.7±49.8	10.8±29.0	20.5	23.1	0.80	47.7
			small	(15.2; 27.7)	(17.9; 29.8)	(0.63; 0.91)	(35.3; 64.4)
EccI	0.86±0.22	0.92±0.23	0.06±0.15	0.11	14.8	0.79	0.25
			small	(0.09; 0.13)	(12.6; 17.4)	(0.65; 0.87)	(0.20; 0.30)
ConI	2.21±0.18	2.20±0.22	0.00±0.12	0.09	3.8	0.82	0.20
			trivial	(0.07; 0.11)	(3.0; 4.7)	(0.66; 0.91)	(0.16; 0.25)
EccV	0.59±0.16	0.64±0.17	0.05±0.12	0.08	16.1	0.76	0.19
			small	(0.07; 0.10)	(13.6; 18.8)	(0.63; 0.84)	(0.16; 0.23)
ConV	1.26±0.16	1.26±0.13	0.00±0.09	0.06	5.8	0.80	0.15
			trivial	(0.05; 0.09)	(4.1; 9.3)	(0.68; 0.91)	(0.12; 0.21)
F@0V	8.7±3.1	9.3±3.2	0.6±2.2	1.6	20.5	0.75	3.7

			trivial	(1.3; 2.1)	(16.2; 26.6)	(0.55; 0.88)	(2.9; 4.9)
DurEcc	0.25±0.10	0.24±0.11	-0.02±0.10	0.07	28.8	0.49	0.17
			small	(0.05; 0.12)	(22.8; 40.4)	(0.14; 0.73)	(0.12; 0.27)
DurCon	0.32±0.07	0.31±0.05	-0.01±0.06	0.04	12.3	0.48	0.10
			trivial	(0.03; 0.07)	(8.0; 20.3)	(0.10; 0.79)	(0.06; 0.17)
CMD	0.30±0.05	0.30±0.06	0.00±0.04	0.03	9.8	0.75	0.06
			trivial	(0.02; 0.04)	(7.5; 13.8)	(0.50; 0.88)	(0.05; 0.09)
Leg stiffness	43.9±9.1	45.0±10.0	1.1±4.3	3.0	7.3	0.90	7.1
			trivial	(2.6; 3.8)	(6.0; 8.8)	(0.82; 0.94)	(5.9; 8.7)
At-PHV maturity group, n=34							
JH	29.0±3.8	28.9±3.7	-0.1±1.6	1.1	4.0	0.91	2.6
			trivial	(0.9; 1.4)	(3.3; 4.9)	(0.84; 0.95)	(2.2; 3.2)
RSImod	0.34±0.08	0.36±0.06	0.01±0.04	0.03	10.2	0.84	0.07
			trivial	(0.02; 0.04)	(7.7; 13.4)	(0.69; 0.92)	(0.05; 0.08)
RFD	126.1±65.0	131.2±60.3	5.1±28.7	20.3	20.5	0.90	47.2
			trivial	(16.5; 26.1)	(15.7; 26.9)	(0.78; 0.95)	(38.3; 60.6)
EccI	0.97±0.18	1.03±0.21	0.06±0.13	0.09	10.1	0.80	0.21
			small	(0.07; 0.11)	(8.0; 12.8)	(0.66; 0.89)	(0.17; 0.26)
ConI	2.44±0.17	2.44±0.16	-0.01±0.13	0.09	3.6	0.71	0.21
			trivial	(0.05; 0.16)	(2.1; 6.6)	(0.22; 0.91)	(0.12; 0.36)
EccV	0.67±0.15	0.70±0.15	0.03±0.12	0.09	12.1	0.67	0.20
			trivial	(0.06; 0.12)	(9.3; 15.9)	(0.47; 0.82)	(0.15; 0.29)
ConV	1.42±0.13	1.42±0.12	0.00±0.06	0.04	3.5	0.87	0.10
			trivial	(0.04; 0.06)	(2.6; 4.9)	(0.75; 0.93)	(0.08; 0.14)
F@0V	11.0±3.1	11.2±2.8	0.2±1.8	1.3	14.0	0.81	3.0
			trivial	(1.0; 1.7)	(10.6; 18.3)	(0.65; 0.91)	(2.3; 3.9)
DurEcc	0.20±0.06	0.18±0.05	-0.01±0.04	0.03	16.1	0.71	0.07
			small	(0.02; 0.04)	(12.4; 20.8)	(0.53; 0.85)	(0.06; 0.10)
DurCon	0.27±0.05	0.26±0.05	-0.01±0.03	0.02	8.5	0.76	0.05
			trivial	(0.02; 0.03)	(6.5; 11.4)	(0.59; 0.87)	(0.04; 0.07)
CMD	0.28±0.06	0.28±0.07	0.00±0.04	0.03	10.6	0.77	0.07
			trivial	(0.02; 0.04)	(8.6; 12.9)	(0.64; 0.85)	(0.06; 0.09)
Leg stiffness	48.4±9.8	46.1±8.2	-2.4±6.6	4.7	10.9	0.74	10.8
			small	(3.8; 6.0)	(9.2; 12.7)	(0.57; 0.84)	(8.9; 13.9)
Post-PHV maturity group, n=42							
JH	34.0±3.6	33.5±3.8	-0.5±1.8	1.3	4.2	0.88	3.0
			trivial	(1.1; 1.5)	(3.5; 5.0)	(0.83; 0.92)	(2.6; 3.6)
RSImod	0.42±0.09	0.40±0.09	-0.01±0.05	0.03	9.4	0.86	0.08
			trivial	(0.03; 0.04)	(7.6; 12.6)	(0.78; 0.91)	(0.07; 0.10)
RFD	153.0±113.1	141.3±78.2	-11.7±73.8	52.2	30.5	0.71	121.3
			trivial	(40.3; 69.5)	(25.4; 37.9)	(0.44; 0.86)	(93.8; 161.7)
EccI	1.06±0.23	1.10±0.21	0.04±0.15	0.10	10.4	0.79	0.24
			trivial	(0.08; 0.13)	(8.7; 12.7)	(0.67; 0.87)	(0.19; 0.31)
ConI	2.66±0.17	2.62±0.16	-0.04±0.11	0.08	3.0	0.79	0.18
			small	(0.06; 0.10)	(2.5; 4.0)	(0.69; 0.86)	(0.14; 0.23)
EccV	0.75±0.18	0.75±0.15	0.00±0.09	0.06	8.5	0.85	0.15
			trivial	(0.05; 0.08)	(7.2; 10.0)	(0.77; 0.90)	(0.13; 0.18)
ConV	1.53±0.10	1.52±0.11	-0.02±0.08	0.05	3.7	0.74	0.12
			trivial	(0.04; 0.07)	(3.0; 4.7)	(0.58; 0.83)	(0.10; 0.16)

F@0V	13.2±4.0	12.4±2.9	-0.9±2.4 small	1.7 (1.4; 2.2)	14.4 (12.1; 17.4)	0.75 (0.62; 0.88)	4.0 (3.3; 5.1)
DurEcc	0.18±0.05	0.18±0.05	0.00±0.03 trivial	0.02 (0.02; 0.03)	13.7 (11.2; 17.4)	0.73 (0.54; 0.85)	0.06 (0.04; 0.07)
DurCon	0.26±0.05	0.27±0.05	0.00±0.03 trivial	0.02 (0.01; 0.02)	6.9 (5.8; 8.3)	0.87 (0.80; 0.92)	0.04 (0.03; 0.05)
CMD	0.31±0.08	0.30±0.07	0.00±0.04 trivial	0.03 (0.02; 0.05)	8.6 (6.7; 12.0)	0.84 (0.71; 0.93)	0.07 (0.04; 0.12)
Leg stiffness	46.1±7.8	44.2±7.8	-1.9±4.3 small	3.0 (2.6; 3.7)	7.5 (6.1; 9.3)	0.85 (0.75; 0.91)	7.2 (6.0; 8.6)

Notes: TE=typical error; CV=coefficient of variation; ICC=intra-class correlation coefficient; SDC=smallest important change at 90% confidence level; mean change is supplemented with qualitative description of standardized differences, exact standardized mean differences can be found in the supplementary file

Self-reported questionnaires to assess physical signs and symptoms as a response to training and competition are widely adopted in professional soccer (Jeffries et al., 2020). However, reliability was purposefully examined in only few studies in adolescent athletes. Results of those studies in late adolescent athletes (16-18 years, no maturity estimate provided) are in agreement with current findings suggesting large between-day variability for single item instruments (CV from 11.2% to 30.0%; ICC from -0.01 to 0.78) (Fitzpatrick et al., 2021; Sawczuk et al., 2018a). Interestingly, our results also showed that reliability differed in relation to the biological maturity status. More specifically, reliability was better across all items for both the pre-PHV and at-PHV compared to the post-PHV cohort, although reliability can still be rated as poor. Besides potential difficulties in comprehension of the underlying constructs and item descriptions across adolescence, reasons for differences between maturity stages may be described by two considerations. First, adolescence reflects a period of substantial psychosocial and emotional changes whereby environmental factors such as family, school and peers impact the psychological well-being differently (Meade & Dowswell, 2016). Therefore, increased external stressors during late adolescence might have therefore resulted in larger between-day variability in self-reported items of the SRSS such as mental performance capability, emotional balance, lack of activation and negative emotional state. Second, despite at least 48 hours of rest prior to testing external and internal loads likely differed between players because of non-training specific physical load such as school or other activities. This in turn might have impacted each athlete's fatigue status and consequently self-reported physical symptoms (e.g., physical performance capability, muscular stress). Taken together, changes of at least 2 points (on a scale from 0 to 6 with 1 point increments) are required to detect meaningful changes, potentially limiting the practical value of the SRSS within the monitoring process.

Table 5.5. Reliability statistics for the submaximal run for the pre-PHV, at-PHV, and post-PHV maturity group.

Variable	Trial 1 (±SD)	Trial 2 (±SD)	Mean change (±SD)	TE (90%CL)	CV (90%CL)	ICC (90%CL)	SDC (90%CL)
Pre-PHV maturity group, n=29							
HRex	178.5±8.9	179.8±8.8	1.2±3.9 trivial	2.7 (2.4; 3.4)	1.6 (1.3; 1.9)	0.90 (0.84; 0.94)	6.4 (5.5; 7.9)
HRR60s	59.7±9.3	59.8±12.7	0.2±11.4 trivial	8.1 (6.6; 10.4)	14.0 (11.2; 19.1)	0.48 (0.18; 0.67)	18.8 (15.3; 24.1)
At-PHV maturity group, n=28							
HRex	174.4±10.8	175.1±10.8	0.7±3.7 trivial	2.6 (2.2; 3.1)	1.5 (1.3; 1.8)	0.94 (0.91; 0.97)	6.1 (5.2; 7.2)
HRR60s	47.9±14.0	47.6±11.6	-0.3±10.3 trivial	7.3 (5.3; 10.8)	16.5 (13.1; 21.5)	0.68 (0.44; 0.82)	17.0 (12.4; 25.3)
Post-PHV maturity group, n=36							
HRex	168.2±11.5	168.1±10.5	-0.2±4.0 trivial	2.8 (2.5; 3.3)	1.7 (1.5; 2.0)	0.93 (0.89; 0.96)	6.6 (5.7; 7.7)
HRR60s	46.7±10.3	48.2±10.3	1.6±7.8 trivial	5.5 (4.6; 7.1)	12.8 (10.4; 15.6)	0.71 (0.54; 0.81)	12.9 (10.6; 16.5)

Notes: TE=typical error; CV=coefficient of variation; ICC=intra-class correlation coefficient; SDC=smallest important change at 90% confidence level; mean change is supplemented with qualitative description of standardized differences, exact standardized mean differences can be found in the supplementary file

Various jump protocols such as the CMJ have been used to examine neuromuscular responses to competition and training. Several studies investigated the reliability of jump height (Buchheit & Mendez-Villanueva, 2013; Fitzpatrick et al., 2021; Sawczuk et al., 2018a), however less attention has been given to CMJ variables related to the movement strategy preceding in adolescent athletes of varying biological maturity. Present results for jump height indicate similar reliability statistics across all maturity groups (CV: 4.0% to 4.7%; ICC: 0.88 to 0.92) that are also in agreement with data previously reported for adolescent athletes ranging from pre-PHV to post-PHV (CV: 4.1% to 4.9%; ICC = 0.86 to 0.94) (Buchheit & Mendez-Villanueva, 2013; Fitzpatrick et al., 2021). As participants were instructed to maximise jump height, this variable can be considered representative of the CMJ "outcome". In contrast, variables related to the eccentric and concentric phase describe the movement strategy preceding the actual outcome. Similar to other investigations, we found larger variability in parameters related to the movement strategy, especially during the eccentric phase (Gathercole et al., 2015; Meylan et al., 2011). Interestingly, we observed a general maturity-gradient whereby better reliability was observed for the post-PHV followed by the at-PHV and pre-PHV cohort. This suggests that maturity-related differences exist during the CMJ which are likely the consequence of a better utilisation of the underpinning adaptations related to the stretch-shortening cycle. With maturation, reduced agonist-antagonist co-contraction, increased tendon stiffness, pre-activation, and reflex control leads to a better stretch-shortening action and in turn more efficient movement (Radnor et al., 2018). Specifically, pre-PHV athletes demonstrated a larger number of Golgi tendon organs increasing afferent activity during high-velocity activities and in turn a greater levels of co-contraction leading to a more variable movement strategy (Frost et al., 1997). As the density and size of Golgi Tendons decrease and undergo a process of desensitisation during maturation, this results in a more efficient stretch-shortening action and in turn better movement strategy and reliability for the at-PHV and post-PHV groups.

Additionally, and somewhat conversely, current results also revealed greater variability in leg stiffness for the at-PHV (CV: 10.9%; ICC = 0.74) compared with the pre- (CV: 7.9%; ICC = 0.90) and post-PHV (CV: 7.5%; ICC: 0.85) cohort. These values are within the ranges of previous investigations of adolescent athletes (Lloyd et al., 2009; Maloney & Fletcher, 2021). As hopping tasks are multi-joint activities they require high levels of neural control and motor coordination (Lloyd et al., 2009). Phases of rapid growth may result in greater variability in the functioning of the pre-motor cortex to constantly adjust and maintain postural control and feedforward mechanisms of the lower limbs leading to disruptions in motor coordination (Lloyd et al., 2012). Importantly, not all adolescent athletes will experience temporary disruptions of motor coordination during phases of accelerated growth (Quatman-Yates et al., 2012). Consequently, the inability of athletes during the growth spurt to consistently coordinate rapid movements that rely on the stretch-shortening cycle leads to a greater variability in leg stiffness.

Monitoring heart rate during and post submaximal running bouts (i.e. HRex, HRR) has gained popularity during recent years as measurement instruments to assess cardiorespiratory fitness and acute response pattern due to its convenient implementation on a daily basis in the practical setting (Buchheit, 2014). Our findings on the reliability of the heart rate responses during the submaximal run (i.e. HRex) supports those previously reported in well trained adolescent and professional senior athletes (Doncaster et al., 2019; Rabbani et al., 2018; Ryan et al., 2019; Veugelers et al., 2016). Variability of HRex was also not affected by maturity status which is in agreement with findings from a previous study on adolescent youth soccer players (Buchheit, Mendez-Villanueva, Quod, et al., 2010). The low between-day variability observed in our study (CV: 1.6% to 1.8%) allows practitioners to detect small changes in both cardiorespiratory fitness and acute response to load of adolescent athletes. Post-exercise HRR revealed larger variability (CV: 12.8% to 15.0%; ICC: 0.48 to 0.71) than HRex. While several studies reported better reliability for HRR in adolescent and senior populations (CV: 3.4% to 7.4%; ICC: 0.60 to 0.84) (Doncaster et al., 2019; Rabbani et al., 2018; Ryan et al., 2019; T. J. Scott et al., 2015), few others reported similar variability (Buchheit, Mendez-Villanueva, Quod, et al., 2010; Owen et al., 2017; Veugelers et al., 2016). Differences in the submaximal running protocol such as preceding prescribed external load (fixed vs. individual velocities) (T. J. Scott et al., 2015), preceding running speed (Lamberts & Lambert, 2009), post-exercise body position (standing vs. sitting) (Buchheit, Al Haddad, et al., 2009), analysis of HRR (reduction in number of heart beats vs. mean heart rate) (Rabbani et al., 2018) might explain these discrepancies across studies. Taken together, HRex during a submaximal running bout might represent a promising, i.e., reliable, measurement in adolescent athletes to monitor acute responses of the cardiorespiratory system, although further work is required to investigate its responsiveness to load.

In the process of monitoring the acute psycho-physiological response to load in adolescent athletes' biological maturation is an important and often over-looked aspect. In the current study a general trend towards larger variability for less mature athletes was observed for tasks requiring a large degree of motor control and coordination. This is of particular importance during adolescence given the large inter-individual variability in biological maturity status within a given age group (Malina et al., 2015). Maturity status has a moderating effect in the magnitude of internal load and therefore presumably post-exercise induced psycho-physiological response despite similar external load accumulation (Salter, Croix, & Hughes, 2021) as it is the case during traditional chronological age group training sessions and competitions. Such differences need to be taken into consideration by practitioners in order to detect real changes that are beyond measurement error for a given athlete. This enables practitioners to determine if acute response trends of an athlete are progressing as initially intended or if the training process needs to be adjusted accordingly. For example, the detection of unplanned large acute negative responses over time in eccentric duration during the CMJ for an athlete who is post-PHV might warrant an intervention (e.g., short recovery period) while acute negative responses of similar magnitude for an athlete who is pre-PHV might be interpreted as measurement error with the training process proceeding as planned. In the context of talent development this is important information for practitioners to accurately interpret acute changes of measurements of load and adequately inform subsequent training sessions. Importantly, while our data provide a framework for smallest detectable changes for MI to assess acute psycho-physiological responses, whether or not such changes are also practically meaningful in relation to minimal important changes requires further investigation.

5.6 Conclusion

The present findings provide new information regarding the reliability of measurement instruments aiming to assess acute psycho-physiological responses to load in relation to biological maturation in youth soccer. They provide a framework for practitioners on measurement variability and meaningful changes of commonly used parameters. However, many investigated variables have poor short-term between-days reliability irrespective of the maturity status questioning their ability to detect small, yet meaningful changes in acute psycho-physiological responses to load. Future studies however should investigate the responsiveness of these measurements to better understand their measurement properties and in turn their practical utility within the monitoring process. Findings of such studies allow practitioners to confidently identify and select measurement instruments, thereby make accurate decisions about the fatigue status of youth soccer players in relation to their biological maturation.

Chapter 6: Are measurement instruments responsive to assess acute responses to load in high-level youth soccer players?

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Are measurement instruments responsive to assess acute responses to load in high-level youth soccer players?

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6.1 Abstract

Purpose: The aim of this study was to assess the short-term responsiveness of measurement instruments aiming at quantifying the acute psycho-physiological response to load in high-level adolescent soccer players.

Methods: Data were collected from 16 high-level male youth soccer players from the Under 15 age group. Players were assessed on two occasions during the week: after two days of load accumulation ("high load") and after at least 48 hours of rest. Measurements consisted of the Short Recovery and Stress Scale (SRSS), a countermovement jump (CMJ) and a sub-maximal run to assess exercise heart-rate (HRex) and heart-rate recovery (HRR60s). Training load was quantified using total distance and high-speed running distance to express external and sRPE training load to express internal load. It was expected that good instruments can distinguish reliably between high load and rest.

Results: Odd ratios (0.74 to 1.73) of rating one unit higher or lower were very low for athlete-reported ratings of stress and recovery of the SRSS. Standardized mean high load vs. rest differences for CMJ parameters were trivial to small (-0.31 to 0.34). The degree of evidence against the null hypothesis that changes are interchangeable ranged from p=0.04 to p=0.83. Moderate changes were observed for HRex (-0.62; 90%CL -0.78 to -0.47; $p = 3.24 \times 10^{-9}$), while small changes were evident for HRR60s (0.45; 90%CL 0.08 to 0.80; p = 0.04). Only small to moderate repeated-measures correlations were found between the accumulation of load and acute responses across all measurement instruments. The strongest relationships were observed between HRex and total distance (rm-r = -0.48; 90%CL -0.76 to -0.25).

Conclusion: Results suggest that most of the investigated measurement instruments to assess acute psycho-physiological responses in adolescent soccer players have limited short-term responsiveness. This questions their potential usefulness to detect meaningful changes and manage subsequent training load and program adequate recovery.

Keywords: training load, fatigue, monitoring, adolescence, responsiveness

6.2 Introduction

Athlete monitoring frameworks are widely implemented and considered as important aspects of the training process to maximise sports performance and health, and in turn minimise injury risk, in professional senior and youth soccer environments. The training process is the systematic repetition of physical training comprising external, i.e., the prescribed quantity and intensity of the training plan, and internal load, i.e., psycho-physiological stress experienced by an athlete during the training session and subsequent associated responses (Jeffries et al., 2021). Conceptually, sports performance can be improved when loading an athlete's biological system to induce adaptive responses. However, stressing the athlete's biological systems has to be balanced with appropriate recovery periods to allow for positive adaptations to occur. This highlights the importance of both measuring and managing training load and the associated acute responses (Impellizzeri et al., 2019).

Response to load is a broader construct encompassing multiple domains including cardiorespiratory, metabolic, neuromuscular, endocrine, musculoskeletal as well as overall functional output (McLaren et al., 2021). Monitoring acute responses to load is commonly used by coaches and practitioners to decide about subsequent training load, evaluate the effectiveness of the training program and prescribe adequate recovery (Salter, Croix, Hughes, et al., 2021; Weston, 2018). This entails a holistic approach involving constructs that are not directly measurable, instead they have to be quantified via surrogate measurement instruments. As such, several measurement instruments are typically selected by coaches and practitioners based on contextual considerations such as specificity to the sport, time efficiency, scalability to large groups, availability, and theoretical aspects such as relevant measurement properties (Coutts, 2014; Robertson et al., 2017; Starling & Lambert, 2018; Thorpe et al., 2017).

Before confidently adopting measurement instruments to assess acute responses to load, several measurement properties need to be assessed and critically appraised to understand whether their quality supports their implementation by practitioners and scientists. Little attention, however, has been given to the responsiveness of parameter and measurements to assess realistically occurring acute responses to load in youth soccer. Responsiveness is defined by the COSMIN panel as the ability of a parameter to detect change over time in the construct to be measured (Mokkink et al., 2010). Responsiveness has been considered as the most important property of measurement instruments (Terwee et al., 2003). Several approaches exist to assess the responsiveness of a given measurement instrument. However, as no gold-standard measurement instruments exist to date to quantify the construct of acute responses to load, a construct-based approach has to be adopted in applied sport science (Vet et al., 2011). That is, repeated measurements are required in which changes in the constructs of interest, i.e., acute responses to load, are expected to occur for some proportion of the participants. The assessment of acute responses after soccer matches or intense training sessions might represent a suitable setting whereby large changes in acute responses are expected for players who accumulated more external and internal loads. The stronger the relationship between both constructs, i.e., accumulated load and acute responses and, the greater the responsiveness for the given measurement instrument.

Few studies have investigated the responsiveness of measurement instruments to assess acute responses to load in professional senior athletes and even fewer in youth populations. Various different methods and measurement instruments have been investigated within late adolescent team sport athletes (Fitzpatrick et al., 2019; Malone, Murtagh, et al., 2015; Noon et al., 2015; Pelka et al., 2018; Sawczuk et al., 2018b). Objective measurement instruments such as squat jump and countermovement jump (CMJ) height appear to lack responsiveness to short periods of intensified load accumulation (Fitzpatrick et al., 2019). No studies, however, have investigated whether parameters related to the kinematics and kinetics of a CMJ are acutely affected after the accumulation of training loads. In contrast, changes in athlete-reported measurements related to the constructs of fatigue and recovery have been observed in response to intense training sessions and matches (Saw, Main, et al., 2016). However, previous research was mainly carried out with athletes during the late adolescence period, ranging from 16 to 19 years of age, or adults. As youth athletes mature from early to late adolescence they experience larger exercise-induced physiological responses to a given load due to changes in muscle mass, fibre type composition, energy metabolism and voluntary activation level occurring during adolescence (Beunen & Malina, 2007; Ratel & Martin, 2015). This is due to the large associated hormonal changes of the hypothalamic-pituitary axes occurring as adolescents enter the phase of peak height velocity directly regulating the maturation of specific structures and tissues (Beunen et al., 2006b). As such responses to load may be maturity-dependent in a way that pre-pubertal children show the smallest responses to load followed by adolescent and adult athletes (Ratel & Williams, 2017). Similarly, youth athletes have to cope with non-spot related stressors such as academic and social issues. Periods of high academic stress potentially superimposes the psycho-physiological responses to load and subsequent physiological adaptation given the lack of adequate coping strategies of youth athletes (Cosh & Tully, 2015). Coaches and practitioners need to be aware of such influencing factors when interpreting psycho-physiological changes to load. This highlights the unique and challenging environment and characteristics of youth athletes aiming to assess responses to load (Scantlebury et al., 2020). Therefore, acute changes to load in athlete-reported measurement instruments within less mature athletes may be smaller, reducing the responsiveness of this measurement instrument.

Therefore, this study aimed to assess the short-term responsiveness of measurement instruments that quantify the acute psycho-physiological response to load in high-level adolescent soccer player. We hypothesise that a few days of accumulated load in adolescent soccer players will (be associated with a) change countermovement jump variables, psychological variables (as measured by the constructs within the Short Recovery and Stress Scale), and heat rate variables derived from a 4-min sub-maximal shuttle run. This information potentially provides practitioners working with youth soccer players additional insight regarding the usefulness of commonly used measurement instruments to assess acute responses to load.

6.3 Methods

6.3.1 Participants

Data were collected from 16 male youth soccer players (chronological age: 14.4±0.3 years, skeletal age: 15.4±1.1 years, 96±3% of predicted adult height, post-pubertal (determined using the BAUS^{TM} system (SonicBone Medical Ltd., Israel) (Ruf et al., 2021)), standing height: 170.0±6.6 cm, body mass: 62.8±9.0 kg) from the Under 15 age group of one professional German youth academy. Testing was conducted during the first half of the 2020/21 season. All participants were medically cleared to participate in formalised soccer practice. Prior to the commencement of the study, all participants were informed about the aims, procedures, and risks of the investigation. Parental or guardian consent for all participants involved in this study was obtained. The study was approved by the institutional ethics committee and was conducted according to the Declaration of Helsinki.

6.3.2 Design

The study comprised a 4-week observational period during the regular in-season period (September to October 2020). A schematic overview is illustrated in Figure 6.1. Players were tested on Friday and Wednesday of the subsequent week before the regular training session (approximately 4:30 to 5:30 pm). In total, 6 testing days were included in the final analysis (three on Wednesday and three on Friday). Testing on Wednesday was scheduled after two days of load accumulation. In contrast, testing on Friday was conducted after at least 48 hours of rest. These testing days were chosen to represent contrasting conditions to maximize the chance for the detection of substantial differences by the measurement instruments assessing the acute responses to the accumulation of high load (Wednesday) vs. rest (Friday). Upon arrival, players filled out the subjective recovery-stress status questionnaire (Short Recovery and Stress Scale, SRSS), performed two CMJs on a force plate, and a sub-maximal run as part of the team training warm-up to calculate heart rate responses during and after the run.

6.3.2.1 Anthropometry and maturation status

Participant’s standing height, body mass and chronological age were measured during the first week of the study. Standing height (± 0.1 cm, seca 213 portable stadiometer, Seca, Hamburg, Germany) and body mass (± 0.1 kg, seca 813, calibrated digital scale, Seca, Hamburg, Germany) were measured according to standardized ISAK measurement techniques (Stewart et al., 2011).

6.3.2.2 Short Recovery-Stress Scale

On testing days, participants completed the German version of the modified Short Recovery and Stress Scale (SRSS) for children/adolescents (SRSS (Kellmann & Kölling, 2020) upon arriving at the training facilities. The questionnaire consists of four items each for the Short Recovery Scale (i.e., Physical Performance Capability, Mental Performance Capability, Emotional Balance, Overall Recovery) and the Short Stress Scale (i.e., Muscular Stress, Lack of Activation, Negative Emotional State, Overall Stress). For each item, a sentence was provided to describe it complementing the four descriptive adjectives. Items were scored on a seven-point Likert scale with single point increments, ranging from does not apply at all (0) to fully applies (6). Structural, construct and cross-cultural validity and strong internal consistency have been reported for both the recovery (α=0.73 to 0.78) and stress scale (α=0.72 to 0.80) in youth and adolescent athletes (Kölling et al., 2019). Reliability of the selected parameters were assessed in a recent short-term between-days reliability study conducted in youth soccer players (Ruf, Drust, Ehmann, Forster, et al., 2022). Coefficients of variations ranged between 18% (Mental Performance Capability) and 52% (Muscular Stress) for the post peak height-velocity group.

6.3.2.3 Countermovement jump (CMJ)

Following a standardized dynamic warm-up consisting of dynamic stretching and sub-maximal jumping, participants performed two CMJs. Participants were required to keep their hands held in place on the hips and instructed to jump as high as possible. CMJ depth and stance were self-selected by the participants. Jumps were performed on a portable dual force plate recording simultaneously vertical forces at 1000 Hz (GEN2 Dual Force Plate, Hawkin Dynamics, Inc., Westbrook, Maine, USA). Left-side and right-side vertical forces were summed to single force-time curves for analysis. Data were collected and stored using the proprietary application (Hawkin Capture, version 7.1.1) on a tablet (Samsung Galaxy Tab A, model number SM-T510, Samsung Electronics Co., Ltd., Suwon, South Korea) connected via Bluetooth to the force plates. Force-time data analysis was done using the proprietary software, which followed the methods previously described by Lake et al. (Lake et al., 2018). The following variables were derived from the force-time data of the CMJ: jump height (JH, cm), reactive strength index modified (RSImod, $m.s^{-1}$), eccentric rate of force development (RFD, $N.s^{-1}$), eccentric impulse (EccI, N.s), concentric impulse (ConI, N.s.), average eccentric velocity (EccV, $m.s^{-1}$), average concentric velocity (ConV, $m.s^{-1}$), force at zero velocity (F@0V, N), duration of eccentric phase (DurEcc, ms), duration of concentric phase (DurCon, ms), countermovement depth (CMD, cm) (for detailed description see supplementary file, see Appendix B, Chapter 10.2.3, Supplementary Table 10.11). Variables from that CMJ with the highest velocity at take-off were used for subsequent analysis. Reliability of the selected parameters were assessed in a recent short-term between-days reliability study conducted in youth soccer players (Ruf, Drust, Ehmann, Forster, et al., 2022). Coefficients of variations ranged between 3.7% (ConV) and 30.5% (RDF) with most parameters showing coefficients of variations smaller than 10% for the post peak-height velocity group.

6.3.2.4 Sub-maximal run

A 4-min continuous shuttle run followed by a 1-min passive (standing) recovery period was performed outdoor at the start of the training session on an artificial turf. Recent research indicated that the assessment of heart rate during sub-maximal runs fluctuates in relation to short-term accumulation of load making this measurement instrument a viable option to monitor cardio-respiratory responses to load (Schneider et al., 2020). All players were tested at the same time. Shuttle distances, times and corresponding average speeds were as follows: 50 m in 15 s at 12.0 km.h^{-1}. After the 4-min continuous shuttle run, players were required to remain in a stationary standing position avoiding any movement. Heart rate was recorded continuously at 1 Hz (Polar Team Pro, Polar Electro Oy, Kempele, Finland) and raw data were subsequently downloaded from manufacturers' proprietary software (Team Pro, version 2.0.4, Polar Electro Oy, Kempele, Finland). Mean heart rate during the final 30 seconds (HRex, beats.min^{-1}) of the 4-min continuous shuttle run was computed (Rabbani et al., 2018). Heart rate recovery was calculated as the absolute difference between HRex and heart rate after the 1-min recovery period (HRR60s, beats.min^{-1}). Reliability of the selected parameters were assessed in a recent short-term between-days reliability study conducted in youth soccer players (Ruf, Drust, Ehmann, Forster, et al., 2022). Coefficients of variations were 1.7% for HRex and 12.8% for the post peak-height velocity group.

6.3.2.5 Training load quantification

External training load was monitored using a global positioning system (GPS). During each training session athletes wore a GPS device (Polar Team Pro; Polar Electro Oy, Kempele, Finland) sampling at 10 Hz. The device was worn on a custom chest belt and athletes were assigned the same device throughout the study period. The following external load variables were selected: total distance (TD, m), high-speed running distance (HSRD, m > 4.7 m.s-1). Internal training load was determined by multiplying the session-rating of perceived exertion (sRPE) by the session duration in minutes to derive sRPE training load (Foster et al., 2001). Following each session, athletes individually reported their sRPE using Borg's modified CR10 scale via a bespoke smartphone application. Ratings were reported at 8 pm, approximately 15 to 30 min following the end of the session. In youth team sports, sRPE has been shown to possess acceptable construct validity as a measure of exercise intensity and internal load (Foster et al., 2021).

6.3.3 Statistical analyses

Data are presented either as mean with standard deviations (SD) or 90% confidence intervals (90% CI). Items of the SRSS were treated as ordinal variables and analysed via ordered logistic regression models (*MASS* package (Venables et al., 2002)). Linear mixed models (*nlme* package (Pinheiro et al., 2019) assessed the changes in CMJ (continuous variables: JH, RSImod, RFD, $N.s^{-1}$, EccI, N.s, ConI, N.s., EccV, $m.s^{-1}$, ConV, $m.s^{-1}$, F@0V, N, DurEcc, DurCon, CMD), and submaximal running heart rate variables (continuous variables: HRex, HRR60s) over the training week (categorical factor, 2 levels: Rest (Friday), High Load (Wednesday)). Correlated random effects were fit by specifying a random intercept for athlete ID and a random slope for time (i.e., Rest and High Load) to account for the individual player difference over the training week. Autocorrelation was specified via the exponential variance-covariance matrix and weights were specified via a constant variance function structure to allow for heterogenous within-subject variances by time (i.e., Rest and High Load).

Changes in the measurement instruments were also assessed by calculating standardized mean differences (SMD, based on Cohen's d's effect size principle using pooled SD). In addition, repeated-measures correlations (rm-r) between changes in the measurement instruments and indicators of external and internal load were computed (*rmcorr* package (Bakdash & Marusich, 2020)). Bootstrapping (with 10000 resamples) was used to derive CIs for SMD and rm-r. Threshold values for SMD were as follows: ≤0.2 (trivial), >0.2-0.6 (small), >0.6-1.2 (moderate), and >1.2 (large). Threshold values for rm-r were as follows: ≤0.10 (trivial), >0.10-0.30 (small), >0.30-0.50 (moderate), >0.50-0.70 (very large), and >0.70-1.00 (excellent). All analysis were performed in Rstudio (version 1.2.5033, RStudio Inc.) with a more detailed outline of the statistical analysis presented in the supplementary material (see Appendix B, Chapter 10.2.3, Supplementary Table 10.12).

6.4 Results

Descriptive data (mean ± SD) for total distance, high-speed running distance and sRPE training load across the data collection period were 10461 ± 2644 m, 821 ± 420 m and 921 ± 274 AU. Daily and accumulated training loads are summarized in Figure 6.1 and Table 6.1.

Descriptive statistics, results of the linear mixed models and standardized mean differences are summarised in Table 6.2 for the items of the SRSS, in Table 6.3 for parameters of the CMJ and Table 6.4 for parameters of the submaximal run. The observed mean changes in the eight parameters of the SRSS ranged from -0.23 to 0.41 (90% confidence intervals -0.51 to 0.74) the degree of evidence against the null hypothesis that the changes are interchangeable ranged from p=0.20 to p=0.98. Trivial to small standardized changes were evident across the parameters of the CMJ. The degree of evidence against the null hypothesis that changes are interchangeable ranged from p=0.04 to p=0.83, indicating large confidence intervals and in turn a wide range of plausible true effects. A moderate (90% confidence interval of [-3.4 to -2.2], $p=5.56 \times 10^{-10}$) decrease in HRex and small (90% confidence interval of [0.5 to 3.8], p=0.02) increase in HRR60s was observed across the two testing assessments.

Repeated-measures correlations between changes in the measurement instruments and indicators of external and internal load revealed small to moderate associations (Figure 6.2). The strongest relationships were observed between HRex and total distance (rm-r = -0.48; 90%CL -0.76 to -0.25), HRR60s and total distance (rm-r = 0.47; 90%CL 0.06 to 0.74), and CMJ concentric impulse and sRPE training load (rm-r = -0.47; 90%CL -0.74 to -0.06).

Table 6.1. Mean ± SD of daily and accumulated training load across the data collection period.

Week	**Loading Pattern**	**Total Distance (m)**		**High-Speed Running Distance (m)**		**sRPE Training Load (AU)**	
		Day 1 Monday	*Day 2 Tuesday*	*Day 1 Monday*	*Day 2 Tuesday*	*Day 1 Monday*	*Day 2 Tuesday*
Week 1	Daily training load	3578 ± 843	6841 ± 1003	39 ± 52	425 ± 160	409 ± 110	516 ± 124
	Accumulated training load	9688 ± 1071		455 ± 126		925 ± 201	
Week 2	Daily training load	5050 ± 666	8164 ± 333	196 ± 69	1025 ± 214	573 ± 162	556 ± 82
	Accumulated training load	12793 ± 1746		1205 ± 262		1081 ± 222	
Week 3	Daily training load	na	8845 ± 2635	na	719 ± 386	na	770 ± 290
	Accumulated training load	8845 ± 2635		719 ± 386		770 ± 290	

6.5 Discussion

The aim of the current investigation was to determine short-term responsiveness of measurement instruments aiming to quantify the acute psycho-physiological response to load in high-level adolescent soccer players. The results of the study demonstrated that 1) magnitudes of changes were trivial to small for athlete-reported ratings of stress and recovery (< 1 AU) and CMJ parameters (0% to 13%) and smaller than the typically observed day-to-day variability (~1 AU for athlete-reported rating of stress and recovery; 3.7% to 30.5% for CMJ parameter), 2) a moderate change with a narrow range for plausible true effects as inferred by the confidence limits, exceeding the typically observed day-to-day variability, was observed for HRex, while a small change was evident for HRR60s, which was however smaller than the typically observed day-to-day variability, and 3) small to moderate relationships were evident between the accumulation of load and acute responses. Collectively, these findings highlight the poor responsiveness of most investigated parameters questioning their potential utility to monitor psycho-physiological responses to load that are beyond the typically observed day-to-day variability in adolescent soccer players. As such, using these measurement instruments to make conclusions on an athlete's psycho-physiological status and in turn to adjust subsequent training loads cannot be recommended.

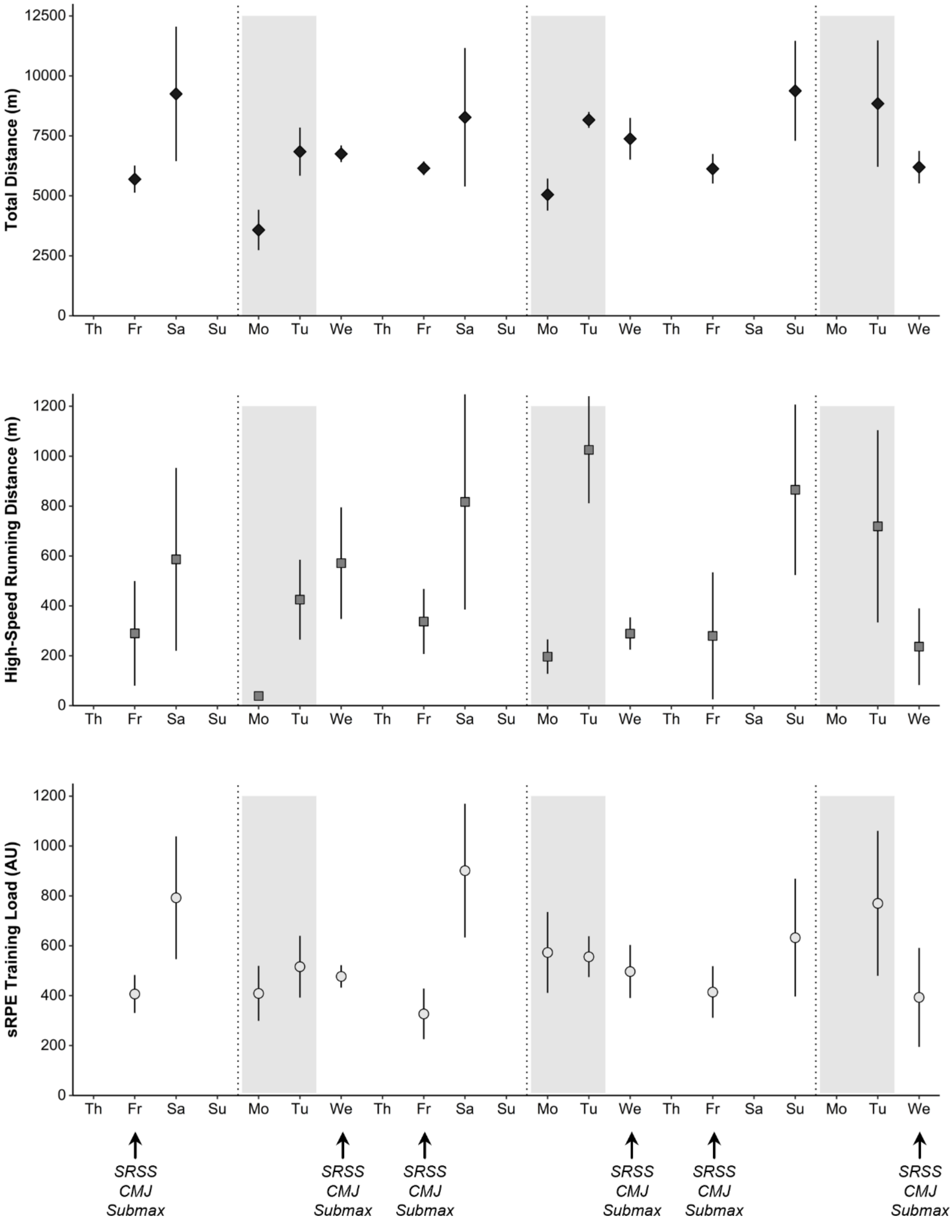

Figure 6.1**.** Mean ± SD of daily training load for sRPE Training Load (upper panel), Total Distance (middle panel) and High-Speed Distance (lower panel) across the study period. The grey area represents the two days of load accumulation. (see methods). Abbreviations: SRSS: Short Recovery and Stress Scale; CMJ: countermovement jump; Submax: sub-maximal run.

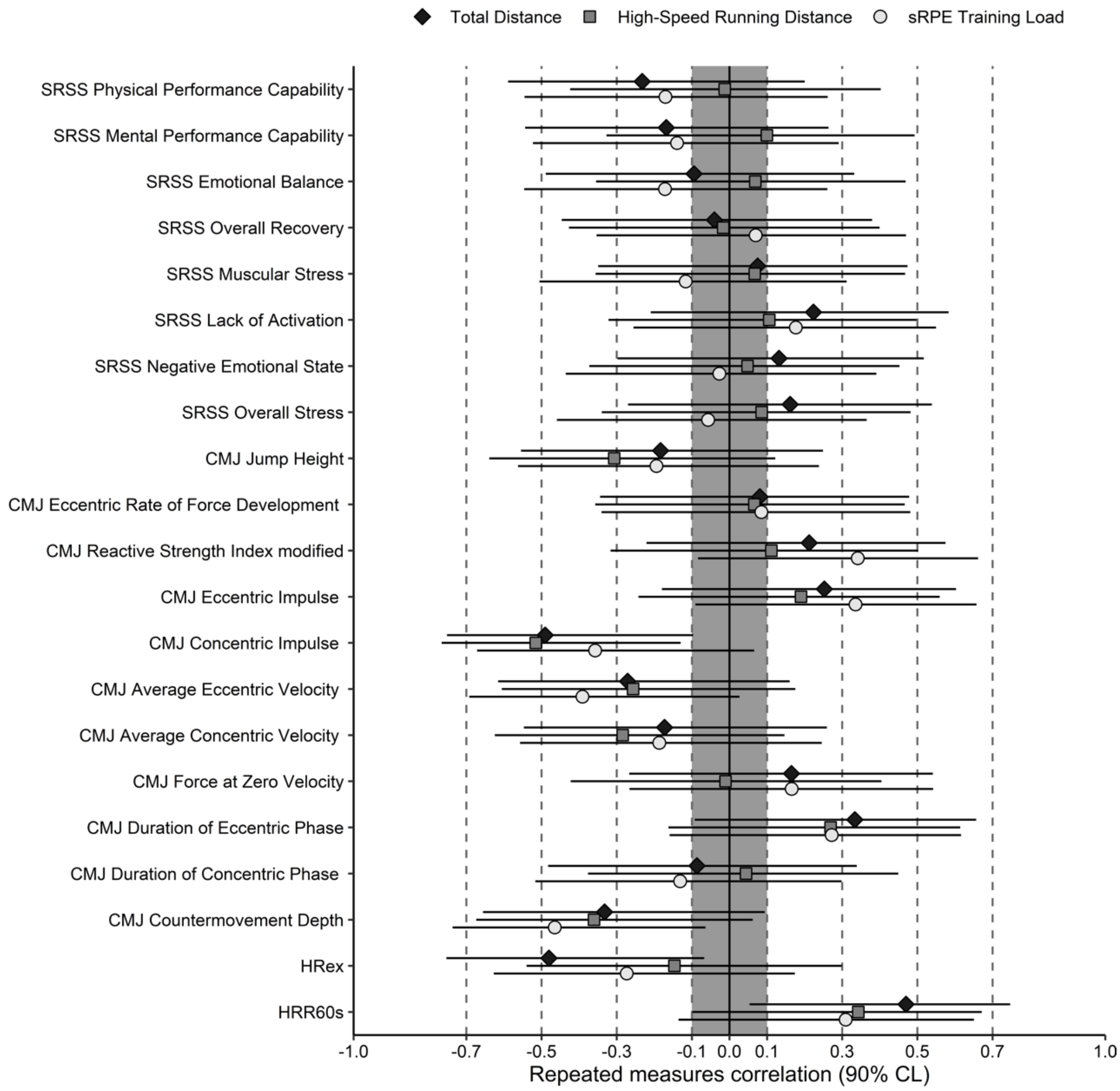

Figure 6.2. Repeated measures correlation (90% CI) between changes in measurement instruments and training load indicators total distance, high-speed running distance and sRPE training load. The grey area represents trivial correlations.

Table 6.2. Descriptive statistics, and odds ratio derived from the ordered logistic regression models of the Short Recovery and Stress Scale (SRSS) (number of observations: 68).

Variable	**Rest** **Frequency count of each rating**	**High Load** **Frequency count of each rating**	**Odds Ratio (90% CI)**	**p value**
Short Recovery Scale				
Physical Performance Capability (AU)	0: 0 1: 0 2: 3 3: 2 4: 7 5: 14 6: 8	0: 0 1: 1 2: 1 3: 8 4: 4 5: 13 6: 7	0.74 (0.35 to 1.54)	0.49

Mental Performance Capability (AU)	0: 0 1: 0 2: 1 3: 5 4: 8 5: 11 6: 9	0: 0 1: 0 2: 2 3: 7 4: 5 5: 12 6: 8	0.83 (0.40 to 1.73)	0.68
Emotional Balance (AU)	0: 0 1: 0 2: 2 3: 2 4: 9 5: 10 6: 11	0: 0 1: 0 2: 3 3: 3 4: 7 5: 10 6: 11	0.93 (0.45 to 1.93)	0.87
Overall Recovery (AU)	0: 0 1: 1 2: 2 3: 5 4: 12 5: 6 6: 8	0: 0 1: 0 2: 6 3: 3 4: 7 5: 13 6: 5	0.99 (0.48 to 2.03)	0.98
Short Stress Scale				
Muscular Stress (AU)	0: 8 1: 10 2: 6 3: 5 4: 4 5: 1 6: 0	0: 7 1: 9 2: 8 3: 5 4: 2 5: 3 6: 0	1.18 (0.57 to 2.42)	0.71
Lack of Activation (AU)	0: 17 1: 8 2: 7 3: 2 4: 0 5: 0 6: 0	0: 13 1: 14 2: 2 3: 2 4: 2 5: 0 6: 1	1.36 (0.64 to 2.88)	0.50
Negative Emotional State (AU)	0: 24 1: 9 2: 0 3: 1 4: 0 5: 0 6: 0	0: 20 1: 10 2: 4 3: 0 4: 0 5: 0 6: 0	1.80 (0.77 to 4.18)	0.25
Overall Stress (AU)	0: 21 1: 4 2: 6 3: 3 4: 0 5: 0 6: 0	0: 16 1: 6 2: 6 3: 3 4: 3 5: 0 6: 0	1.83 (0.83 to 3.98)	0.20

Note: *Rest* refers to the testing scheduled on Friday, which was conducted after at least 48 hours of rest; *high load* refers to the testing scheduled on Wednesday, which was conducted after two days of load accumulation; *mean change* refers to the absolute difference between high load and rest; CI=confidence interval

Table 6.3. Descriptive statistics, standardized mean differences and results of the linear mixed models for parameters of the countermovement jump (CMJ) (number of players: 16; number of observations: 68; df: 51).

	Jump height (cm)	**Reactive strength index modified ($m.s^{-1}$)**	**Eccentric Rate of Force Development ($N.s^{-1}.kg^{-1}$)**	**Eccentric Impulse ($N.s.kg^{-1}$)**	**Concentric Impulse ($N.s.kg^{-1}$)**	**Eccentric Velocity ($m.s^{-1}$)**	**Concentric Velocity ($m.s^{-1}$)**	**Force at Zero Velocity ($N.kg^{-1}$)**	**Duration of Eccentric Phase (ms)**	**Duration of Concentric Phase (ms)**	**Countermovement Depth (cm)**
Predictors											
Rest mean±SD	33.2±4.2	0.40±0.07	85.7±35.4	2.7±0.5	5.0±0.5	-0.72±0.14	1.52±0.12	22.8±2.7	168±44.4	250±47.1	-28.3±5.7
High Load mean±SD	32.9±3.9	0.39±0.07	74.6±29.7	2.8±0.4	5.0±0.5	-0.73±0.16	1.50±0.11	22.1±2.4	176±35.6	254±43.3	-29.1±6.0
Intercept (90% CI)	0.33 (0.31 to 0.35	0.40 (0.37 to 0.42)	84.9 (72.7 to 97.2)	2.7 (2.5 to 2.9)	5.0 (4.8 to 5.2)	-0.72 (-0.78 to -0.66)	1.52 (1.47 to 1.57)	22.8 (21.7 to 23.9)	170 (152 to 187)	250 (231 to 270)	-28.3 (-30.8 to -25.8)
Mean change High Load minus Rest (90% CI)	-0.25 (-0.75 to 0.28)	-0.10 (-0.03 to 0.01)	-11.1 (-23.9 to 1.4)	0.1 (-0.0 to 0.2)	0.0 (-0.0 to 0.1)	0.00 (-0.03 to 0.03)	-0.02 (-0.04 to 0.00)	-0.7 (-1.7 to 0.1)	8 (-4 to 21)	4 (-3 to 11)	-0.76 (-1.7 to 0.2)
p value	p = 0.37	p = 0.13	p = 0.07	p = 0.15	p = 0.48	p = 0.56	p = 0.12	p = 0.08	p = 0.28	p = 0.36	p = 0.16
Standardized mean difference (90% CI)	-0.06 (-0.18 to 0.07)	-0.14 (-0.38 to 0.09)	-0.31 (-0.59 to -0.02)	0.19 (-0.02 to 0.37)	0.06 (-0.08 to 0.19)	-0.03 (-0.19 to 0.11)	-0.16 (-0.35 to 0.05)	-0.28 (-0.58 to 0.00)	0.18 (-0.05 to 0.45)	0.08 (-0.08 to 0.24)	-0.13 (-0.27 to 0.01)
Random Effects											
SD residual (90% CI)	1.27 (0.96 to 1.67)	0.06 (0.03 to 0.10)	17.3 (14.5 to 21.2)	0.23 (0.16 to 0.31)	0.19 (0.15 to 0.25)	0.10 (0.06 to 0.17)	0.06 (0.04 to 0.07)	2.3 (1.0 to 5.2)	44 (8 to 225)	19 (15 to 24)	2.3 (1.9 to 2.7)

Between-subject-SD τ00 (90% CI)	4.1 (3.0 to 5.6)	0.05 (0.02 to 0.12)	30.2 (21.7 to 43.2)	0.46 (0.33 to 0.61)	0.47 (0.36 to 0.67)	0.12 (0.06 to 0.19)	0.12 (0.08 to 0.16)	1.6 (0.3 to 8.3)	38 (23 to 50)	45 (32 to 60)	5.4 (4.0 to 7.6)
Random-slope-SD τ11 (90% CI)	0.4 (0.02 to 0.8)	0.02 (0.006 to 0.07)	24.8 (14.8 to 38.0)	0.18 (0.10 to 0.30)	0.02 (0.005 to 0.14)	0.02 (0.005 to 0.10)	0.03 (0.06 to 0.11)	1.7 (1.2 to 2.6)	20 (6 to 32)	4 (1 to 25)	0.41 (0.08 to 1.8)
Phi parameter (90% CI)	0.09 (-0.46 to 0.59)	0.63 (0.06 to 0.89)	-0.04 (-0.39 to 0.33)	0.36 (-0.12 to 0.71)	0.08 (-0.28 to 0.41)	0.83 (0.60 to 0.93)	0.11 (-0.31 to 0.50)	0.79 (0.10 to 0.96)	0.86 (-0.44 to 0.99)	-0.05 (-0.36 to 0.28)	0.04 (-0.26 to 0.34)

Note: *Rest* refers to the testing scheduled on Friday, which was conducted after at least 48 hours of rest; *high load* refers to the testing scheduled on Wednesday, which was conducted after two days of load accumulation; *mean change* refers to the absolute difference between high load and rest; CI=confidence interval; SE=standard error; df=degrees of freedom

Table 6.4. Descriptive statistics, standardized mean differences and results of the linear mixed models for parameters of the submaximal run (number of players: 16; number of observations: 68; df: 49).

	HRex (%)	**HRR60s (%)**
Predictors		
Rest mean±SD	87.6±4.4	23.3±4.5
High Load mean±SD	84.8±4.7	25.4±5.4
Intercept (90% CI)	87.6 (85.8 to 89.4)	23.4 (21.7 to 25.1)
Mean change High Load minus Rest (90% CI)	-2.8 (-3.4 to -2.2)	2.1 (0.5 to 3.8)
p value	$p = 5.56 \times 10^{-10}$	p = 0.02
Standardized mean difference (90% CI)	-0.62 (-0.78 to -0.47)	0.45 (0.08 to 0.80)
Random Effects		
SD residual (90% CI)	1.5 (1.3 to 1.7)	3.7 (3.2 to 4.4)
Between-subject-SD τ00 (90% CI)	4.1 (2.9 to 5.5)	2.8 (1.5 to 4.7)
Random-slope-SD τ11 (90% CI)	0.3 (0.003 to 0.9)	0.7 (0.001 to 3.1)
Phi parameter (90% CI)	-0.10 (0.40 to 0.22)	-0.02 (-0.38 to 0.34)

Note: *Rest* refers to the testing scheduled on Friday, which was conducted after at least 48 hours of rest; *high load* refers to the testing scheduled on Wednesday, which was conducted after two days of load accumulation; *mean change* refers to the absolute difference between high load and rest; CI=confidence interval; SE=standard error; df=degrees of freedom

The current study is one of the first to investigate the relationship between training load indicators and acute psycho-physiological responses in adolescent soccer players. Findings of this study support previous studies that identified a limited responsiveness of measurement instruments that aim to quantify the acute psycho-physiological response to load in adolescent athletes (Fitzpatrick et al., 2019; Sawczuk et al., 2018b). This is in contrast to a recent systematic review suggesting that athlete-reported measurement instruments have a better responsiveness to acute training load than objective measures in adults (Saw, Main, et al., 2016). In addition, adolescent athletes experience non-sport related stressors such as academic and social pressures potentially impacting the perception of recovery and stress. However, changes in all items of the SRSS were less than one point which is less than the typical day-to-day variability observed in youth soccer players (typical error of measurement: ~1 point), and less than the minimal detectable change which is one point on a seven-point ordered scale since that is the minimal possible measurement unit (Ruf, Drust, Ehmann, Forster, et al., 2022), accompanied with low odds of players rating one unit higher or lower on the scale. Similarly, correlations between training load and items of the SRSS were ranged between trivial to small. Discrepancies in these findings can potentially be attributed to the inherent differences between the two populations. Adolescent athletes have a unique set of psychological and physiological characteristics and environmental circumstances. As youth athletes mature towards adulthood the substantial physiological changes create larger exercise-induced responses to load (Ratel & Martin, 2015; Ratel & Williams, 2017). However, given that adolescence marks a critical period of emotional and cognitive development with the largest changes occurring in the development of executive functions (i.e., abstract thinking, decision making and planning, and response inhibition (Yurgelun-Todd, 2007). This potentially reduces the ability of the adolescent athlete to efficiently and effectively express and reproduce perceptions associated with recovery and stress (Steinberg, 2005). Although daily external and internal training loads were slightly lower in professional soccer players, evidence suggests that academy soccer players do not achieve the absolute intensities completed by elite adult soccer players (Malone, Di Michele, et al., 2015b). Our results suggest that training load has only a trivial to small impact on athlete-reported levels of stress and recovery in youth soccer players, but more research from different age groups and in turn biological maturity is needed to confirm this finding.

Another interesting finding of this study was that whilst we observed some moderate within-player associations between accumulated training load indicators and changes in CMJ parameters, magnitudes of these observed changes were mostly trivial to small. Similar to previous research (Fitzpatrick et al., 2019; Noon et al., 2018; Sawczuk et al., 2018b) CMJ jump height did not show substantial changes and associations with training load indicators supporting the notion that jump height is a poor parameter to assess responses to load. It has therefore been suggested to examine the responsiveness of parameters reflecting the kinematics and kinetics of the CMJ (Gathercole et al., 2015). However, we observed only small to moderate associations of accumulated training load and changes in most eccentric and concentric kinematic and kinetic parameters. In particular, increased training load was associated with moderate decreases in concentric impulse and somewhat contradictory small to moderate increases in force at zero velocity and rate of force development, respectively. However, force at zero velocity and rate of force development were, on average, both impaired after the two days of load accumulation. While it is difficult to ascertain the underlying mechanisms of these findings a reasonable explanation of this might relate to the impaired contractile function (i.e., force capacity, blood flow) and muscle activation (i.e., voluntary activation, neuromuscular propagation) (Enoka & Duchateau, 2016) as a result of the inflammatory process after high-eccentric loading which typically peaks between 24 to 48 h after a training stimulus (Nédélec et al., 2012). In addition, altered stretch-reflex sensitivity and muscle-tendon stiffness have been reported after eccentric loading protocols resulting in reduced force and power production (Nicol et al., 2006). This ultimately reduces mechanical efficiency resulting in altered kinematics and kinetics, particularly for parameters of the CMJ related to the eccentric phase (Byrne et al., 2004). Taken together, the small to moderate associations and changes in CMJ parameters observed in this and previous studies (Fitzpatrick et al., 2019; Norris et al., 2021; Sawczuk et al., 2018a) highlight the difficulty and complexity of assessing neuromuscular responses to load. In addition, despite small to moderate standardised changes, confidence intervals of the absolute changes were rather large and mean absolute changes in CMJ parameters were smaller than the typical day-to-day variability observed in a recent between-day reliability study (Ruf, Drust, Ehmann, Forster, et al., 2022) questioning their usefulness to detect small changes that are beyond the naturally evident variability of these parameters in high-level adolescent soccer players. As such, the observed changes in CMJ parameters are likely underpowered given the variability in the data failing to observe detectable changes that are beyond the typically observed day-to-day-variability. Future research might therefore look into employing training load indicators measuring more accurately the external and internal neuromuscular loads to ascertain the potential responsiveness of CMJ parameters in relation to periods of increased neuromuscular training loads. In this context, both short- (e.g. training camp) and long-term periods (e.g., pre-season) are of interest to evaluate the acute and chronic responsiveness of the CMJ in particular and measurement instruments in general.

Finally, we observed a moderate decrease in HRex and small increase in HRR60s after two days of load accumulation. While the observed change in HRex (~-2.8%) was substantially greater than the reported day-to-day variations previously reported within similar populations (typical error of measurement: ~1.5%), day-to-day variability for HRR60s (typical error of measurement: 7-16%) exceeded by far the observed change in our study (2.1%) (Doncaster et al., 2019; Rabbani et al., 2018; Ruf, Drust, Ehmann, Forster, et al., 2022). Only small changes in HRR60s have also been previously reported despite simultaneous substantial decreases in HRex during an eleven day in-season camp in the heat (Buchheit et al., 2011). Similarly, HRex was substantially reduced after several consecutive training days across a 12-week intensified preparatory period in elite Badminton players (Schneider et al., 2020). In addition, we observed a moderate correlation between changes in HRex and total distance. This is consistent with previous observational research from training camps in senior Gaelic Football and soccer, whereby daily changes in HRex were strongly correlated with changes in training load (Buchheit, Racinais, et al., 2013; S. Malone et al., 2017). The stronger correlations observed in these studies likely reflect the greater day-to-day fluctuations in training load and in turn greater range of changes in HRex. Importantly, while a decreased HRex has also been shown to be associated with chronic improved cardiorespiratory fitness after several weeks (e.g. (Altmann et al., 2021; Buchheit et al., 2012)), in the context of short-term responses to load, decreases in HRex are likely the result of exercise-induced increases in plasma volume (Schneider et al., 2020). In addition, decreased HRex has been shown to be associated with changes in cardiac autonomic nervous system such as lower sympathetic and higher parasympathetic activity, reduced catecholamine tissue responsiveness and adrenergic receptor activity (Buchheit, Laursen, et al., 2009; Meeusen et al., 2013). Similar to HRex, the strongest correlation for HRR60s with moderate magnitude was observed with total distance. Post-exercise heart rate recovery generally reflects metaboreflex activity, which partly influences parasympathetic reactivation and sympathetic withdrawal during the initial phase of recovery (Borresen & Lambert, 2008; Buchheit, 2014). This suggests that even greater accumulated training loads are required to elicit substantial changes in the autonomic nervous system and in turn HRR60s after short periods of load accumulation. Our and previous findings suggest that using heart rate during exercise should be preferred to heart rate recovery after submaximal runs to monitor acute cardiorespiratory responses to load.

Limitations of the current study also need to be acknowledged. Although our training load indicators matched the commonly used ones (Nosek et al., 2021) it cannot be ruled out that either (1) training load indicators are unable to provide an accurate estimate of the mechanical demands to reflect subsequent acute psycho-physiological responses (Vanrenterghem et al., 2017), (2) the psycho-physiological response measurement instruments lack responsiveness to fluctuations to training load or (3) the fatiguing period was not high enough to elicit substantial psycho-physiological responses. Further, given the applied nature of the study design, chronic responses resulting from supercompensation effects across the study period were not considered. In addition, physical capacities (e.g., aerobic and anaerobic endurance, strength and power) in combination with other individual characteristics (e.g., biological maturation status) may act as a moderator in the acute responses to load and should therefore warrant consideration when interpreting the responsiveness of the investigated measurement instruments. Further, as training load was not controlled and documented on the day off (i.e., Thursday), players might have engaged in non-football specific physical activity impacting the measurement after the rest day. Finally, data were collected only on a small sample from a single age group of one club as a result of the applied nature of this study which may not be representative to other youth athletes of different biological maturity or from other clubs.

6.6 Practical application

This study provides practitioners with a better understanding of the relationships between indicators of training load and common measurement instruments to quantify acute responses to load in adolescent soccer players. Our findings suggest that the limited responsiveness of athlete-reported questionnaires and CMJ parameters means that these measurement instruments are unlikely to provide insight into the acute psycho-physiological responses to load. As such, practitioners utilizing athlete-reported questionnaires and CMJ parameters to quantify acute psycho-physiological responses to load should do so with caution while exploring other measurement instruments to provide more nuanced insights into the constructs of fatigue and recovery. In contrast, HRex during a submaximal run reflects acute responses of the cardiorespiratory system to load and might therefore be used by practitioners to manage training load or program adequate recovery. However, changes in HRex need to be interpreted within the context of the training program as acute negative and chronic positive cardiorespiratory changes follow the same pattern.

6.7 Conclusion

Taken together, our results suggest that most of the investigated measurement instruments to assess acute psycho-physiological responses have limited short-term responsiveness to training load. As such, these measures provide limited information for practitioners when evaluating the psycho-physiological response of adolescent soccer players to training load. Future studies should investigate the chronic responsiveness of measurement instruments for adolescents of varying maturity status in order to better understand the usefulness of such parameters to manage subsequent training load and recovery more effectively.

Chapter 7: Psycho-physiological responses to a pre-season training camp in high-level youth soccer players

This study has been accepted for publication following peer review in the *International Journal of Sports Physiology and Performance*. The content has been reformatted for the purposes of this thesis. The full reference details of this published study are:

Psycho-physiological responses to a pre-season training camp in high-level youth soccer players

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7.1 Abstract

Purpose: This study aimed to examine the responsiveness of commonly used measurement instruments to a short training camp by examining the time-course of psycho-physiological responses in high-level youth soccer players.

Methods: Monitoring was carried out in 14 U15 male soccer players of one professional youth academy. Players provided data three days prior to (D-3), during (D2 to D4), as well as one (D+1) and four days (D+4) after the camp: Short Recovery and Stress Scale (SRSS) consisting of four items for the Short Recovery and Stress Scale, a countermovement jump (CMJ), and a sub-maximal run to assess exercise heart rate (HRex) and heart rate recovery (HRR60s). Training load during the camp followed an alternating low-high pattern, with lower training loads on D1 and D3 and higher training loads on D2 and D4.

Results: Changes in SRSS Physical Performance Capability, Emotional Balance, and Overall Recovery and SRSS Muscular Stress and Overall Stress were small to moderate on D3 and moderate to large on D+1, while changes were trivial on D+4. Some CMJ parameters related to the eccentric phase were slightly improved on D3, these parameters were slightly impaired on D4. Changes in CMJ parameters were trivial on D+1 and D+4. After a moderate decrease in HRex on D3, there was a small decrease on D+4, and a moderate increase in HRR60s.

Conclusion: Measurement instruments such as the SRSS and sub-maximal runs can be used to monitor acute psycho-physiological responses to load, while the CMJ may provide little insight during periods of intensified training load.

Keywords: adolescence, training camp, fatigue, monitoring, training load

7.2 Introduction

From a physical perspective the main goal of pre-season preparation in soccer is to develop the physical qualities and prepare players for the competitive season (Clemente et al., 2021). The underlying concept of improving physical qualities is that an athlete's biological systems are temporarily overloaded to induce adaptive responses. Typically, more training time is therefore dedicated to elicit positive physiological adaptations during this period compared to within the season where the focus shifts towards technical and tactical development in youth soccer (Maughan et al., 2021). To avoid maladaptive training outcomes particularly during intensified periods such as the pre-season, monitoring athletes psycho-physiological responses to load is critical to guide the overall training process (Jeffries et al., 2021).

Psycho-physiological responses resulting from exercise-induced stress are the antecedents of functional adaptations in any physical quality (Viru & Viru, 2000). The quantification of the response to load is challenging as there are no gold standard parameters (Impellizzeri et al., 2019; Jeffries et al., 2021). Therefore, the response must be quantified by surrogate measurements reflecting biological systems that are of interest to the practitioner to make informed decisions about adjusting the training plan. Given the complexity and breadth of psycho-physiological responses to load, researchers and practitioners adopt a holistic approach by applying a multitude of parameters to determine how athletes are coping with the demands and in turn to avoid negative training outcomes (Jeffries et al., 2021). Typically, these include the neuromuscular, musculoskeletal, endocrine, metabolic, cardiorespiratory system and athlete-reported questionnaires measuring constructs such as recovery, stress, fatigue or soreness (McLaren et al., 2021). Several studies examined the impact of fluctuations in daily training load on changes in selected measurements during periods of increased training load such as pre- and in-season camps within elite senior team sports (Buchheit et al., 2016; Buchheit, Simpson, et al., 2013; Malone et al., 2017). Collectively, these studies showed the practicality and usefulness of time-efficient and non-invasive measurement instruments such as athlete-reported questionnaires (e.g., reflecting constructs such as fatigue, recovery and stress), functional performance tests (e.g., countermovement jump (CMJ) performance), and submaximal fitness tests (e.g., heart rate responses during and after the sub-maximal run) to monitor psycho-physiological responses to load. Reliability and validity of those measurement instruments to assess the underlying constructs in youth soccer players has been evaluated previously (Altmann et al., 2022; Kölling et al., 2019; Ruf, Drust, Ehmann, Forster, et al., 2022; Ruf, Drust, Ehmann, Skorski, et al., 2022). The CMJ analysis is often limited to performance-outcome parameters such as jump height and peak power. This may overlook how athletes potentially alter their strategy to execute the jump which may be reflected in kinematic (e.g., duration of eccentric phase) and kinetic parameters (e.g., force at zero velocity) of the different phases of the jump, which can be derived from the force-time data of the CMJ. The usefulness of those CMJ parameters requires further examination as it has been previously suggested that these parameters might provide a greater insight into the underpinning neuromuscular mechanisms at play (Gathercole et al., 2015). Further, submaximal fitness tests provide a pragmatic approach to evaluate the cardiorespiratory fitness by assessing the heart rate response (i.e., exercise heart rate (HRex) and heart rate recovery (HRR)) to a standardised physical stimulus without inducing undue exhaustion. While changes in exercise heart rate (HRex) might be reflective of both acute responses to load and chronic improvements in cardiorespiratory fitness (Buchheit, 2014; Schneider et al., 2020), little information exists regarding HRR as a potential valuable parameter to monitor acute cardiorespiratory response to load. Despite the potential usefulness of the aforementioned parameters to monitor acute responses to load during intensified pre- and in-season periods in elite adult team sport populations (Buchheit et al., 2016; Buchheit, Simpson, et al., 2013; Malone et al., 2017), it is still unknown whether these parameters can also be confidently used in the context of adolescent soccer players. Several additional moderating factors need to be considered in the context of youth athletes. For example, biological maturation has been shown to influence neuromuscular responses after standardised and regular training sessions in U13 to U16 youth soccer players (Salter, Croix, & Hughes, 2021; Salter et al., 2022). Similarly, training age might potentially also impact the acute psycho-physiological response within this population.

Training camps during the pre-season period are common in elite senior and youth soccer teams to facilitate positive adaptations (Buchheit et al., 2016; Buchheit, Simpson, et al., 2013). During pre-season training camps in elite senior sports, training load is typically higher compared to periods during the regular pre-season period (Thornton et al., 2016). For instance, in Gaelic football and Rugby League, weekly training load indicators during the training camp were increased by approximately 50 % to 130 % (Malone et al., 2017; Thornton et al., 2016). In addition, several other environmental stressors such as travel, altitude, or heat may provide additional physical stress impacting the overall psycho-physiological status of elite senior athletes (Buchheit et al., 2016; S. Malone et al., 2017; Pitchford et al., 2017; Thornton et al., 2016). Therefore, substantial acute psycho-physiological responses to load can be expected to occur. As such, these periods are a suitable setting to assess the responsiveness of measurement instruments, despite the small sample sizes and single-club setting involved in this type of research potentially limiting the generalisation to other age groups and clubs. Responsiveness can be defined in this context as the ability of a parameter to detect changes over time in the respective construct and has been considered an important aspect in the evaluation of the overall usefulness of a parameter (Mokkink et al., 2010). However, currently it is unclear how short intensified periods of increased training load, such as training camps impact acute psycho-physiological responses of adolescent soccer players. An answer would allow coaches to select those measures that are responsive to changes in training load enabling them to optimize training load distribution before and during intensified periods.

Therefore, the aim of the current study was to investigate the responsiveness of commonly used measurement instruments to a typical pre-season period including a short training camp by examining the time-course of psycho-physiological responses in high-level youth soccer players.

7.3 Methods

7.3.1 Participants

Data were collected from 14 male youth soccer players (mean ± standard deviation (SD): chronological age: 14.3±0.3 years, skeletal age: 15.0±1.2 years, standing height: 167.9±8.0 cm, body mass: 55.8±8.1 kg) belonging to the U15 age group of one professional German youth academy. Participants can be classified as Tier 3 athletes: Highly Trained/National Level according to the Participant Classification Framework (McKay et al., 2022). Upon enrolment, parents/guardians signed contracts providing consent confirming that data arising as a condition of regular player monitoring procedures can be used for research purposes. The study was approved by the institutional ethics committee of Saarland University (registration number: 20-18) and was conducted according to the Declaration of Helsinki.

7.3.2 Study design

The training camp took place 7 weeks after the start of the pre-season period and 4 weeks before the start of the season. Players travelled for four hours by bus to and from the camp. Three days prior to the camp, players performed a baseline assessment after at least 48 h of complete rest (i.e., *D-3 Pre-Camp*) and had one additional training session the day before the departure (Figure 7.1). During the 4-day camp (i.e., *D1 Camp to D4 Camp*), players took part in four training sessions and one tournament on the last day comprising of 7 matches of 20 min each. On D2, there were two training sessions scheduled, while on D1 and D3 there was only one training session. Assessments were conducted on the second (i.e., *D2 Camp*), third (i.e., *D3 Camp*) and fourth day (i.e., *D4 Camp*). After the camp players were given three days off, with post-assessments conducted on the first (i.e., *D+1 Post-Camp*) and fourth day after the camp (i.e., *D+4 Post-Camp*) while no training sessions were performed during this period. Although D+4 was logistically driven and additional assessments would provide further insight into the recovery time-course, the aim was to determine if a three day rest period is sufficient for players to return back to or exceed baseline scores. Assessments prior to and after the camp were conducted prior to the actual training session (i.e., 5:00 to 5:45 pm), while assessments during the camp were conducted upon awakening and prior to the training sessions or matches (i.e., 8:30 to 9:30 am). Due to the club's policy, players were not allowed to consume dietary supplements throughout the study period. The assessment battery consisted of the modified Short Recovery and Stress Scale (SRSS) for children/adolescents (Kellmann & Kölling, 2020), a countermovement jump (CMJ), and a sub-maximal run (exercise heart rate, HRex; heart rate recovery, HRR60s).

7.3.3 Procedures

Standing height (± 0.1 cm, seca 213 portable stadiometer, Seca, Hamburg, Germany) and body mass (± 0.1 kg, seca 813, calibrated digital scale, Seca, Hamburg, Germany) were measured one week prior to the training camp. The BAUS™ system (SonicBone Medical Ltd., Israel) was used to assess skeletal age four weeks prior to the training camp as previously described (Ruf et al., 2021). Air temperature and relative humidity were noted at the start of every training session to calculate a heat index (HI).

Upon awakening players filled out the German version of the modified Short Recovery and Stress Scale (SRSS) for children/adolescents (Kellmann & Kölling, 2020; Kölling et al., 2019). The questionnaire consists of four items for the Short Recovery Scale (i.e., Physical Performance Capability (smallest detectable change at 90% confidence level (SDC, calculated as $1.645\ x\ \sqrt{2}\ x\ standard\ error\ of\ measurement$) derived from a short-term between-days reliability study conducted in youth soccer players (Ruf, Drust, Ehmann, Forster, et al., 2022), SDC: 0.9), Mental Performance Capability (SDC: 1.1), Emotional Balance (SDC: 1.0), Overall Recovery (SDC: 1.9)) and the Short Stress Scale (i.e., Muscular Stress (SDC: 2.1), Lack of Activation (SDC: 1.4), Negative Emotional State (SDC: 1.5), Overall Stress (SDC: 1.9)). For each item a sentence was provided to describe the respective item complementing the four descriptive adjectives. Item was rated on a seven-point Likert scale with single point increments, ranging from does not apply at all (0) to fully applies (6). Construct validity and internal consistency have been confirmed for both the recovery (α=0.73 to 0.78) and stress scale (α=0.72 to 0.80) in youth and adolescent athletes (Kölling et al., 2019).

Prior to the regular training sessions, players performed two CMJs following a brief standardized dynamic warm-up consisting of dynamic stretching and two sub-maximal jumps. Players were required to keep their hands held on their hips and were instructed to jump as high as possible. CMJ stance width and countermovement depth were self-selected by the players. CMJs were performed on a portable force plate recording vertical forces at 1000 Hz (GEN2 Dual Force Plate, Hawkin Dynamics, Inc., Westbrook, Maine, USA). Force-time data were collected and analysed using the proprietary software (Hawkin Capture, version 7.1.1), which followed the methods previously described (Lake et al., 2018). The following variables were selected from the force-time data of the CMJ with the highest velocity at take-off: jump height (JH, cm, SDC: 2.6), reactive strength index modified (RSImod, $m.s^{-1}$, SDC: 0.07), eccentric rate of force development (RFD, $N.s^{-1}.kg^{-1}$, SDC: 47), eccentric impulse (EccI, $N.s.kg^{-1}$, SDC: 0.2), concentric impulse (ConI, $N.s.kg^{-1}$, SDC: 0.2), average eccentric velocity (EccV, $m.s^{-1}$, SDC: 0.2), average concentric velocity (ConV, $m.s^{-1}$, SDC: 0.1), force at zero velocity (F@0V, $N.kg^{-1}$, SDC: 3), duration of eccentric phase (DurEcc, ms, SDC: 73), duration of concentric phase (DurCon, ms, SDC: 55), countermovement depth (CMD, cm, SDC: 7.1) (for detailed description see supplementary file, see Appendix B, Chapter 10.2.4, Supplementary Table 10.13).

As part of the warm-up for the actual training session, a 4-min continuous sub-maximal shuttle run (shuttle distance: 50 m) at 12.0 $km.h^{-1}$ followed by a 1-min passive (standing) recovery period was performed as previously described (Ruf, Drust, Ehmann, Forster, et al., 2022). Running speed was controlled by an audio signal (i.e., whistle). Heart rate was recorded continuously at 1 Hz (Polar Team Pro, Polar Electro Oy, Kempele, Finland) with the average heart rate during the final 30 seconds (HRex, $beats.min^{-1}$, SDC: 6) and the absolute difference between HRex and heart rate after the 1-min recovery period (HRR60s, $beats.min^{-1}$, SDC: 17) used for analysis. All values for the SDC were derived from a recent short-term between-days reliability study conducted in youth soccer players (Ruf, Drust, Ehmann, Forster, et al., 2022).

External training load during training sessions and matches was quantified using GPS units sampling rate at 10 Hz (Polar Team Pro; Polar Electro Oy, Kempele, Finland). Total distance (m) and high-speed running distance ($m > 4.7\ m.s^{-1}$) were selected for analysis. Internal training load was determined by multiplying the session-rating of perceived exertion (sRPE) by the duration in minutes to derive sRPE training load (sRPE-TL) (Foster et al., 2001). Athletes individually reported their sRPE using Borg's modified CR10 scale via a bespoke smartphone application. Acceptable construct validity of the sRPE as a measure of internal load has been reported in a variety of youth team sports (Foster et al., 2021).

7.3.4 Statistical analyses

Data are presented as mean with SD or 90% confidence intervals (90% CI). Linear mixed models (*lme4* package) were used to assess the changes in psycho-physiological responses across the study period relative to baseline (i.e., *D3*). Individual player ID and skeletal age were specified as random effects to allow for different within-subject SDs by the use of random intercepts and slopes. Assessment day was added as fixed factor. Statistical significance of coefficients was assessed using the Satterthwaite's degrees of freedom method (*lmerTest* package). Statistical significance was set at $p < 0.05$. Changes in the measurement instruments were also assessed by calculating standardized mean differences (SMD, based on Cohen's d's effect size principle using the pooled SD). Threshold values for SMD were as follows: ≤0.2 (trivial), >0.2-0.6 (small), >0.6-1.2 (moderate), and >1.2 (large). All analyses were performed in Rstudio (version 1.2.5033, RStudio Inc.).

7.4 Results

Daily training load for sRPE-TL, total distance, and high-speed distance across the three time periods (Pre-Camp, Camp, and Post-Camp) are shown in Figure 7.1. In total, players covered on average 33739±2918 m with 855±315 m of high-speed with a sRPE-TL of 3577±467 AU during the camp. Training load during the camp followed an alternating low-high pattern, whereby training loads were low on *D1* and *D3* and high on *D2* and *D4*, respectively. The average heat index during the camp was 28.5±3.3°C.

Table 7.1. Descriptive statistics (mean ± SD), standardized mean differences (SMD with 90% confidence intervals, 90% CI) and results of the linear mixed models (p values) for the items of the Short Recovery and Stress Scale (SRSS). Changes are presented relative to baseline (i.e., *D-3 Pre-Camp*).

Parameter	D-3 Pre-Camp mean±SD	D2 Camp mean±SD SMD (90%CI) p value	D3 Camp mean±SD SMD (90%CI) p value	D4 Camp mean±SD SMD (90%CI) p value	D+1 Post-Camp mean±SD SMD (90%CI) p value	D+4 Post-Camp mean±SD SMD (90%CI) p value
Short Recovery Scale						
Physical Performance Capability (AU)	4.9±0.7	4.4±1.2 -0.51 (-1.14; 0.13) p = 0.96	4.5±1.0 -0.42 (-1.04; 0.22) p = 0.71	4.9±1.0 0.08 (-0.54; 0.71) p = 0.98	3.6±1.1 -1.35 (-2.04; -0.65) p = 0.0038*	4.9±0.8 0.10 (-0.53; 0.72) p = 0.99
Mental Performance Capability (AU)	5.0±0.9	4.9±1.0 -0.08 (-0.70; 0.55) p = 1.00	4.8±1.0 -0.23 (-0.85; 0.40) p = 1.00	5.2±0.8 0.26 (-0.37; 0.88) p = 0.78	4.5±0.9 -0.55 (-1.18; 0.09) p = 0.63	5.1±0.9 0.08 (-0.54; 0.70) p = 0.99
Emotional Balance (AU)	5.2±0.9	5.0±1.0 -0.22 (-0.84; 0.40) p = 0.95	4.6±1.0 -0.67 (-1.31; -0.03) p = 0.26	5.2±0.8 0.00 (-0.62; 0.62) p = 1.00	4.6±1.0 -0.67 (-1.31; -0.03) p = 0.41	5.2±0.9 0.00 (-0.62; 0.62) p = 1.00
Overall Recovery (AU)	4.7±0.9	4.1±1.1 -0.57 (-1.19; 0.07) p = 0.60	4.1±1.1 -0.65 (-1.28; 0.00) p = 0.35	4.6±1.2 -0.13 (-0.75; 0.49) p = 1.00	3.4±1.1 -1.36 (-2.04; -0.65) p = 0.003*	4.9±1.0 0.15 (-0.48; 0.77) p = 0.99
Short Stress Scale						
Muscular Stress (AU)	1.1±1.0	1.5±1.3 0.37 (-0.26; 1.00) p = 0.48	2.1±1.2 0.90 (0.24; 1.55) p = 0.09	1.9±1.5 0.63 (-0.02; 1.26) p = 0.18	2.9±1.3 1.63 (0.89; 2.34) p = 0.0003*	1.1±0.9 0.07 (-0.55; 0.69) p = 1.00
Lack of Activation (AU)	0.9±1.4	0.6±1.0 -0.18 (-0.80; 0.45) p = 0.96	0.8±1.1 -0.06 (-0.68; 0.57) p = 1.00	0.4±0.8 -0.38 (-1.00; 0.25) p = 0.87	1.0±1.0 0.12 (-0.50; 0.74) p = 1.00	0.6±0.9 -0.18 (-0.80; 0.45) p = 0.96
Negative Emotional State (AU)	0.5±0.7	0.7±1.1 0.24 (-0.38; 0.86) p = 0.77	0.6±0.6 0.11 (-0.51; 0.73) p = 1.00	0.5±0.9 0.00 (-0.62; 0.62) p = 1.00	0.7±0.8 0.29 (-0.34; 0.91) p = 0.98	0.5±0.9 0.00 (-0.62; 0.62) p = 1.00
Overall Stress (AU)	0.9±1.1	1.1±0.9 0.14 (-0.49; 0.76) p = 1.00	1.3±1.2 0.30 (-0.32; 0.93) p = 0.97	0.8±1.1 -0.13 (-0.75; 0.50) p = 0.99	2.3±1.1 1.23 (0.54; 1.90) p = 0.036*	0.8±1.0 -0.13 (-0.76; 0.49) p = 0.99

Abbreviations: SMD: standardized mean difference; CI: confidence interval; Note: * indicates a significant change ($p < 0.05$) relative to *D-3 Pre-Camp*

Table 7.1 summarises all data for all items of the SRSS across the study period, while Table 7.2 and Table 7.3 display all data for the CMJ and sub-maximal run, respectively. Supplementary Figure 10.1 (see Appendix B, Chapter 10.2.4) visually displays mean and individual data for all CMJ parameters across the three time periods (pre-camp, camp, and post-camp). For detailed results of all linear mixed models see supplementary file, see Appendix B, Chapter 10.2.4, Supplementary Table 10.14, Supplementary Table 10.15, Supplementary Table 10.16.

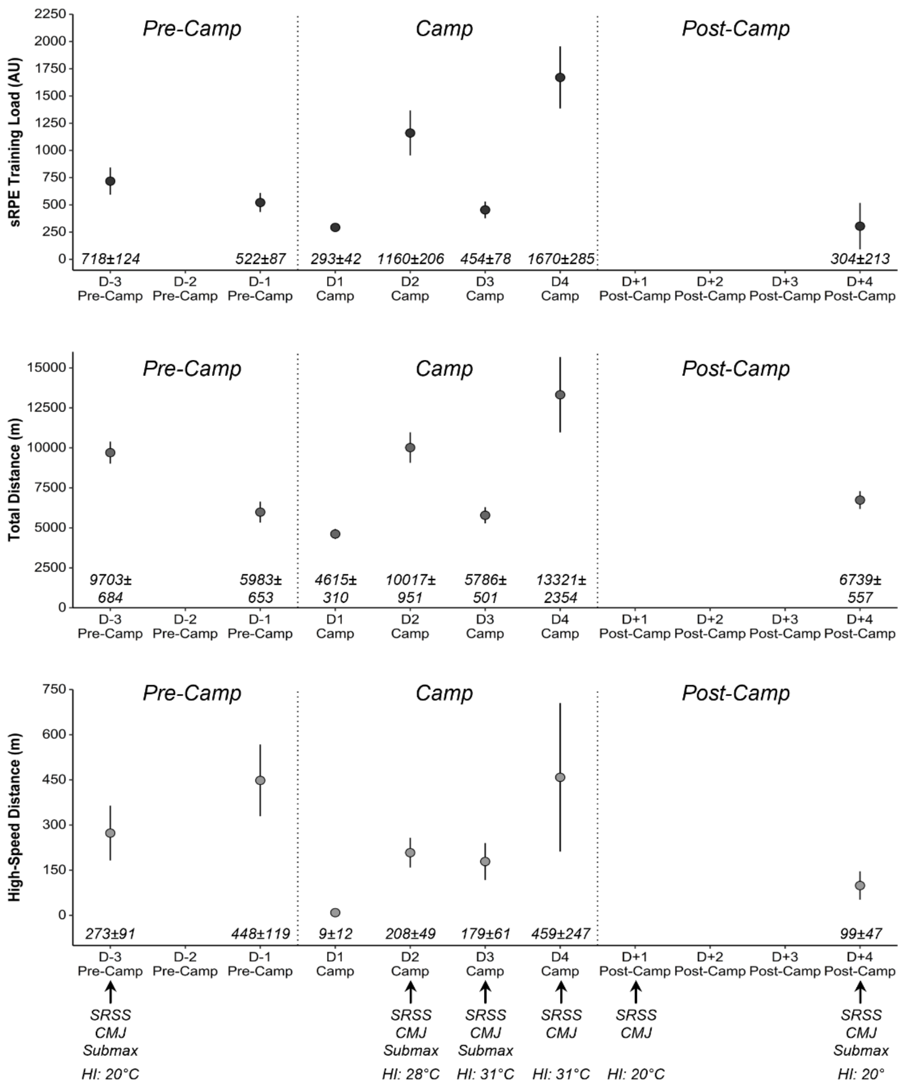

Figure 7.1. Mean ± SD of daily training load for sRPE Training Load (upper panel), Total Distance (middle panel) and High-Speed Distance (lower panel) across the three time periods (pre-camp, camp, and post-camp) as well as the heat index (HI) for each day. Abbreviations: SRSS: Short Recovery and Stress Scale; CMJ: countermovement jump; Submax: sub-maximal run; HI: heat index.

Relative to the baseline changes in SRSS items were trivial to small on *D2*. On *D3* changes in SRSS physical, emotional, and overall recovery as well as SRSS physical and overall stress were small to moderate, while on *D4* changes in all SRSS items were trivial expect for SRSS Mental Performance Capability (small impairment) and SRSS Muscular Stress (moderate impairment). Substantial impairments were observed for SRSS Physical Performance Capability, Overall Recovery, Muscular Stress and Overall Stress *D+1*, *w*hile changes were trivial on *D+4*.

On *D3* there were small improvements in some CMJ parameters (i.e., Jump Height, Reactive Strength Index modified, Eccentric Impulse, Eccentric Velocity, Concentric Velocity). While some CMJ parameter related to the eccentric phase were slightly impaired on *D4* (i.e., Eccentric RFD, Eccentric Impulse, Eccentric Velocity, Force at Zero Velocity, Duration of Eccentric Phase), the majority of changes in CMJ parameters were trivial on *D+1* and *D+4.*

After a moderate decrease in HRex on *D3*, HRex was slightly decreased and HRR60s moderately increased on *D+4.*

Table 7.2. Descriptive statistics (mean ± SD), standardized mean differences (SMD with 90% confidence intervals, 90% CI) and results of the linear mixed models (p values) for parameters of the countermovement jump (CMJ). Changes are presented relative to baseline (i.e., *D-3 Pre*-Camp).

Parameter	D-3 Pre-Camp mean±SD	D2 amp mean±SD SMD (90%CI) p value	D3 Camp mean±SD SMD (90%CI) p value	D4 Camp mean±SD SMD (90%CI) p value	D+1 Post-Camp mean±SD SMD (90%CI) p value	D+4 Post-Camp mean±SD SMD (90%CI) p value
Jump Height (cm)	31.4±4.5	32.7±4.4 0.29 (-0.34; 0.92) p = 0.96	32.9±4.5 0.34 (-0.29; 0.97) p = 0.47	30.6±4.5 -0.17 (-0.79; 0.45) p = 0.99	31.3±4.4 -0.02 (-0.64; 0.60) p = 1.00	32.0±4.1 0.15 (-0.48; 0.77) p = 0.97
Reactive strength index modified ($m.s^{-1}$)	0.36±0.08	0.40±0.07 0.43 (-0.20; 1.06) p = 0.80	0.36±0.06 0.35 (-0.28; 0.98) p = 0.82	0.36±0.06 -0.08 (-0.71; 0.54) p = 1.00	0.38±0.09 0.15 (-0.47; 0.77) p = 0.98	0.37±0.06 0.04 (-0.59; 0.66) p = 0.99
Eccentric RFD ($N.s^{-1}.kg^{-1}$)	8.3±2.9	8.9±3.3 0.20 (-0.42; 0.82) p = 0.97	8.5±3.3 0.07 (-0.55; 0.69) p = 0.99	7.3±3.1 -0.32 (-0.94; 0.31) p = 0.58	7.8±3.5 -0.15 (-0.77; 0.48) p = 0.90	8.2±2.7 -0.02 (-0.64; 0.60) p = 0.99
Eccentric Impulse ($N.s.kg^{-1}$)	3.0±0.4	3.0±0.4 -0.09 (-0.71; 0.53) p = 1.00	3.2±0.4 0.34 (-0.29; 0.96) p = 0.80	3.2±0.5 0.31 (-0.32; 0.93) p = 0.73	3.1±0.4 0.21 (-0.41; 0.83) p = 0.78	3.0±0.4 -0.04 (-0.66; 0.58) p = 1.00
Concentric Impulse ($N.s.kg^{-1}$)	5.3±0.4	5.3±0.4 -0.15 (-0.77; 0.47) p = 0.99	5.4±0.4 0.08 (-0.55; 0.70) p = 0.99	5.3±0.4 0.02 (-0.60; 0.64) p = 1.00	5.3±0.5 0.03 (-0.59; 0.65) p = 0.99	5.4±0.4 0.11 (-0.51; 0.73) p = 0.99
Eccentric Velocity ($m.s^{-1}$)	-0.87±0.10	-0.89±0.10 -0.17 (-0.79; 0.45) p = 0.94	-0.93±0.11 -0.54 (-1.16; 0.10) p = 0.67	-0.84±0.13 0.25 (-0.38; 0.87) p = 0.81	-0.86±0.12 0.09 (-0.54; 0.71) p = 0.99	-0.87±0.12 0.01 (-0.61; 0.63) p = 1.00
Concentric Velocity ($m.s^{-1}$)	1.50±0.12	1.51±0.12 0.07 (-0.55; 0.69) p = 1.00	1.55±0.12 0.37 (-0.26; 1.00) p = 0.45	1.47±0.12 -0.27 (-0.89; 0.36) p = 0.88	1.48±0.15 -0.15 (-0.77; 0.47) p = 0.93	1.51±0.11 0.08 (-0.54; 0.70) p = 1.00
Force at Zero Velocity ($N.kg^{-1}$)	2.4±0.3	2.4±0.3 0.10 (-0.53; 0.72) p = 0.99	2.4±0.3 0.15 (-0.48; 0.77) p = 0.99	2.3±0.3 -0.36 (-0.99; 0.27) p = 0.62	2.3±0.3 -0.23 (-0.85; 0.40) p = 0.84	2.4±0.2 -0.13 (-0.75; 0.50) p = 0.99
Duration of Eccentric Phase (ms)	178±30	169±31 -0.29 (-0.91; 0.34) p = 0.91	181±38 0.09 (-0.53; 0.72) p = 1.00	194±49 0.40 (-0.23; 1.02) p = 0.79	184±37 0.20 (-0.43; 0.82) p = 0.88	174±28 -0.13 (-0.75; 0.49) p = 0.98
Duration of Concentric Phase (ms)	290±38	279±37 -0.29 (-0.92; 0.34) p = 0.98	288±41 -0.06 (-0.68; 0.56) p = 1.00	295±45 0.10 (-0.52; 0.72) p = 0.99	292±49 0.04 (-0.58; 0.66) p = 1.00	293±47 0.05 (-0.57; 0.67) p = 1.00
Countermovement Depth (cm)	-35.6±4.6	-34.7±4.7 0.19 (-0.43; 0.81) p = 1.00	-37.4±5.8 -0.34 (-0.96; 0.29) p = 0.94	-35.6±5.9 0.01 (-0.62; 0.63) p = 0.99	-35.0±4.6 0.13 (-0.49; 0.75) p = 0.99	-34.9±6.0 0.12 (-0.50; 0.74) p = 0.99

Abbreviations: SMD: standardized mean difference; CI: confidence interval; Note: * indicates a significant change ($p < 0.05$) relative to *D-3 Pre-Camp*

7.5 Discussion

The aim of this study was to examine the responsiveness of commonly used parameters by examining the time-course of psycho-physiological responses in relation to changes in training load during a 4-day pre-season camp in high-level youth soccer players. The results showed that i) the SRSS items and heart rate parameters followed a somewhat similar pattern whilst CMJ parameters did not follow the same pattern of responses, ii) there were only trivial to small changes in CMJ parameters throughout the camp highlighting its limited usefulness to monitor potential acute neuromuscular responses to load, and iii) there were substantial cardiorespiratory responses during the camp (i.e., HRex). Collectively, our findings show that athlete-reported parameters such as the SRSS and sub-maximal runs reflect changes in training load during and after an intensified training camp and, thus, are candidate indicators for practitioners to base decisions about training load on.

Table 7.3. Descriptive statistics (mean ± SD), standardized mean differences (SMD with 90% confidence intervals, 90% CI) and results of the linear mixed models (p values) for parameters of the sub-maximal run. Changes are presented relative to baseline (i.e., *D-3 Pre-Camp*).

Parameter	D-3 Pre-Camp mean±SD	D2 Camp mean±SD SMD (90%CI) p value	D3 Camp mean±SD SMD (90%CI) p value	D4 Camp mean±SD SMD (90%CI) p value	D+1 Post-Camp mean±SD SMD (90%CI) p value	D+4 Post-Camp mean±SD SMD (90%CI) p value
HRex (bpm)	185±8.1	184±7.3	179±7.2	-	-	182±8.5
		-0.19 (-0.81; 0.43)	-0.91 (-1.55; -0.24)			-0.49 (-1.12; 0.15)
		p = 0.72	p = 0.002*			p = 0.05
HRR60s (bpm)	46±10.5	48±11.1	48±12.5	-	-	55±16.6
		0.18 (-0.44; 0.80)	0.18 (-0.44; 0.81)			0.67 (0.02; 1.30)
		p = 0.75	p = 0.98			p = 0.02*

Abbreviations: SMD: standardized mean difference; CI: confidence interval; Note: * indicates a significant change ($p < 0.05$) relative to *D-3 Pre-Camp*

Athlete-reported measurement instruments such as the SRSS have previously been shown to be responsive in relation to changes in training load (Buchheit et al., 2016; Schneider et al., 2020). We observed a similar trend whereby moderate impairments were evident for Emotional Balance and Overall Recovery as well as Muscular Stress on *D3* and large impairments were evident for Physical Performance Capability and Overall Recovery as well as Muscular Stress and Overall Stress on *D+1* similar to recent findings in elite senior Badminton players during an in-season training period (Schneider et al., 2020). Both *D3* and *D+1* followed the two training days with the highest training loads suggesting that these items provide practitioners with the most useful information regarding a player's perceived response related to the constructs of recovery and fatigue (Kölling et al., 2015). Items reflecting mental recovery as well as mental and emotional stress are considerably less affected by large increases in training load consistent with previous findings from a 5-day training camp in youth hockey (Kölling et al., 2015). However, given the unlikely substantial changes in these items, practitioners might put special emphasis on players reporting large impairments in one of these items to avoid undesirable developments in mental and emotional health. Despite evidence regarding its validity in adolescent athletes, adolescence is a variable period for various neurobiological processes characterise by high inter-individual differences in cognitive and affective development (Yurgelun-Todd, 2007). As such, athlete-reported measurement instruments relying on subjective perceptions might be interpreted with caution within this population given the potential lack of body awareness. Nevertheless, athlete-reported measurement instruments encompass several constructs and domains that are not objectively measurable providing unique insight into the acute responses to load of an athlete (McLaren et al., 2021).

Notably, on *D3* some CMJ parameters including jump height were slightly improved. However, on *D4* small impairments in the same CMJ parameters were evident, while athlete-reported SRSS scores were restored. This suggests that in adolescent soccer players subjective (i.e., SRSS) and objective measurement instruments (i.e., CMJ) follow different acute response patterns, although the CMJ might not provide valuable insight into neuromuscular responses to load within adolescent athletes potentially due to its low task-specificity (Silva et al., 2018). In fact, the inflammatory process as a result of muscle damage peaks between 24 and 48 h after a training stimulus (Nédélec et al., 2012), which likely caused the delayed impairments in CMJ parameters. Conversely, athlete-reported recovery and stress scores tend to be restored within 24 h highlighting the importance to adapt a holistic athlete monitoring system including both subjective and objective measurement instruments as they represent different biological constructs (Jeffries et al., 2021). Such information has to be taken into consideration when planning subsequent training days to avoid maladaptive training outcomes or even overload, particularly during intensified periods such as the pre-season (Impellizzeri et al., 2020).

Although we observed some changes in CMJ parameters reflecting the kinematics and kinetics of the eccentric phase of the CMJ (e.g., on *D4*), these were rather small. While difficult to decipher the real reasons, this might highlight the limited responsiveness and in turn usefulness of these parameters to monitor acute neuromuscular responses to load in this specific population (Fitzpatrick et al., 2019). Alternatively, even greater training loads are necessary to elicit substantial acute neuromuscular changes as players were coping well with the imposed demands during the camp (Norris et al., 2021). Whether or not similar neuromuscular response patterns of the CMJ or other more run-specific objective performance tests can be observed in even younger (i.e., pre-pubertal) and older (i.e., post-pubertal) adolescent soccer players requires further research. Notwithstanding the on average small changes, practitioners observing players with unexpected large reductions in CMJ parameters might implement additional recovery strategies or adjust subsequent training loads to maximise sport performance and health.

Finally, players showed substantial cardiorespiratory responses during the camp on *D3* (i.e., decreased HRex). While acute changes in HRex can be indicative of exercise-induced plasma expansion (Buchheit, Laursen, et al., 2009), the decreased HRex and increased HRR60s after the camp indicate clear fitness improvements (Buchheit, 2014). The magnitude of decrease in HRex (~2.2 % maximal heart rate) was somewhat smaller compared to previously reported pre-season camps in elite senior soccer players (~3-8 % maximal heart rate) (Buchheit et al., 2011, 2016). However, longer camp lengths and additional heat exposure (Gibson et al., 2020) likely explain the greater changes in fitness after the camp in these studies. Besides tracking fitness improvements, it has been suggested that HRR60s is also a viable parameter to monitor acute responses to load in endurance athletes (Buchheit, 2014). In fact, previous studies showed that changes in heart rate recovery were strongly related to weekly training load (Borresen & Lambert, 2007). However, our data indicated that there was no meaningful change of HRR60s during the camp. Heart rate recovery reflects metaboreflex activity, which drives sympathetic withdrawal and parasympathetic reactivation following exercise cessation (Daanen et al., 2012). The lack of substantial changes in HRR60s during the camp in our study suggests that the training camp might have been too short and training load might not have been high enough to elicit substantial changes in the autonomic nervous system. Nevertheless, the moderate increase in HRR60s after the camp suggests that players showed small to moderate fitness improvements after the short intensified period (Daanen et al., 2012).

Despite adding valuable insights into the time-course of psycho-physiological responses to a short pre-season camp in high-level youth soccer players, several limitations must be acknowledged. Firstly, given logistical constraints, it was not possible to perform the sub-maximal run on *D4* and *D+1*, which would have provided further insight into cardiorespiratory responses after a training day of low and high training load. Secondly, the lack of a (laboratory-based) multistage incremental test to assess cardiorespiratory capacity precludes the interpretation of decreased HRex and increased HRR60s after the camp as small to moderate improvements in cardiorespiratory fitness. However, recent studies in elite senior soccer players highlighted the high agreement of changes in heart rate responses during a sub-maximal run and lactate threshold suggesting that sub-maximal runs are a valid, cost-effective, and more practical method to assess cardiorespiratory fitness (Altmann et al., 2021). Thirdly, whilst total distance, high-speed distance and sRPE-TL are commonly used training load indicators in both research and practice (Akenhead & Nassis, 2016), they might not accurately reflect the external and internal neuromuscular demands (Vanrenterghem et al., 2017). As such, it is unclear whether the small changes in CMJ parameters are a result of the limited responsiveness of the CMJ or a lack of sufficiently high neuromuscular training load. Future research may employ more sophisticated external and internal training load indicators reflecting the neuromuscular system in order to further examine the potential usefulness of the CMJ to monitor acute neuromuscular responses to load. Finally, given the applied nature of this study data were obtained only on a small sample from a single age group of one club. Findings might therefore not be generalisable to other youth athletes of different biological maturity or from other clubs.

7.6 Practical application

The present data suggest that simple, cost-effective, and non-invasive athlete-reported parameters such as items related to the Physical Performance Capability, Emotional Balance and Overall Recovery as well as Muscular Stress and Overall Stress of the SRSS and a sub-maximal run to assess heart rate responses can be used to monitor constructs such as recovery and stress and cardiorespiratory responses to load during and after a period of increased training load. Practitioners can therefore use such indicators to help making informed decisions on programming adequate recovery and adjusting subsequent training loads. In the context of this study, parameters derived from a CMJ, however, add little value.

7.7 Conclusion

This study contributes to a better understanding of the responsiveness of commonly used measurement instruments for load changes during a short training camp in high-level youth soccer players. Small to moderate changes in the athlete-reported recovery and stress scales of the SRSS and heart rate responses during the sub-maximal run were observed in temporal relation to changes in training load during the camp. Only trivial to small changes in CMJ parameters were documented highlighting its potential limited responsiveness to detect meaningful responses to load. After the camp, following a 3-day break, players were fully recovered and showed small to moderate improvements in cardiorespiratory fitness. Whether these benefits differ if the camp were organised differently (e.g., length, altitude, heat etc.) remains to be investigated.

Chapter 8: General Discussion

This chapter provides a general discussion of the thesis including a summary of the findings of the included studies, methodological considerations, recommendations for future research, and practical applications for implementing an athlete monitoring framework in a high-level youth soccer environment.

8.1 Summary of findings

The overarching aim of this thesis was to firstly compare a new device that measures skeletal age to a previously established method of percentage of predicted adult height as two potential practical, non-invasive methods to assess biological maturation status and secondly evaluate the measurement properties of reliability and responsiveness of commonly used measurement instruments to monitor acute psycho-physiological responses to load in youth soccer players. The main findings of this thesis can be summarised as follows:

1) A novel device based on ultrasound-technique to measure skeletal age can be used to assess biological maturity status with a maturity-related selection bias towards players advanced in biological maturation emerging in the U14 age group.

2) Reliability of measurement instruments aiming to assess acute responses to load was relatively poor irrespective of the maturity status, although there was a maturity-related gradient, whereby reliability statistics were generally better for the post-PHV group followed by the at-PHV and pre-PHV group.

3) Responsiveness was poor after regular in-season training sessions for most investigated parameters except for HRex derived from a submaximal run, while athlete-reported parameters such as the SRSS and HRex might respond well to changes in training load during and after periods of a short-term pre-season training camp of intensified training load.

These findings have important implications for both research and practice and can guide future research that aims to advance the field of monitoring acute responses to load in youth soccer players. This may help practitioners in more accurately prescribing training load to elicit the desired adaptations and potentially mitigating injury risk in the long-term. Therefore, the aim of this section is to critically discuss the various implications arising from the studies of this thesis.

8.1.1 Assessment of biological maturation

The assessment of biological maturation in the applied setting of high-performance programs is challenging. While several methods exist ranging from somatic, sexual, and skeletal protocols, all of them have limitations when it comes to the actual implementation (Malina et al., 2015). For example, the two most commonly used somatic maturity protocols include the percentage of predicted adult height and predicted maturation offset (Salter, Croix, Hughes, et al., 2021). While the former relies on anthropometrical characteristics of the biological parents, which are not always readily available, the latter has been shown to provide unreliable and invalid estimations (Malina, 2017). Similarly, traditional radiographs to measure skeletal maturity are no practical and ethical alternatives within the applied setting given their associated constraints and limitations. Therefore, Chapter 4 aimed to assess the construct validity of a novel device based on ultrasound-technique to measure skeletal age to facilitate the objective assessment of biological maturity within high-performance programs. Findings of Chapter 4 indicate that both skeletal age as derived from the BAUS™ system and percentage of predicted adult height were almost perfectly interrelated demonstrating the construct validity of both methods to assess biological maturity status. Similar results have been found in previous and subsequent studies investigating the validity of the BAUS™ system against a well-established reference criterion such as standard radiograph and magnetic resonance imaging (Leyhr et al., 2020; Rachmiel et al., 2017). Results were also comparable to previous studies investigating the interrelationship between skeletal (using standard radiographs) and somatic (using percentage of predicted adult height) maturity (Hill et al., 2019; Malina, Dompier, et al., 2007; Malina et al., 2012). This allows practitioners to objectively measure skeletal age within the applied setting without the typically associated limitations of traditional standard radiographs. The implementation of a robust method to assess biological maturation provides a solid foundation and helps practitioners to guide the overall training process. Caution is, however, warranted when using and comparing maturity status classifications between different methods given the somewhat arbitrarily thresholds used to classify athletes as early, on-time, and late maturing. Maturity classification is standard procedure in both research (Figueiredo et al., 2009a; Materne et al., 2021; Monasterio et al., 2022; Myburgh et al., 2019) and practice (McBurnie et al., 2021). To avoid any loss and statistical power in the analysis, it is however recommended to avoid using a uniform threshold to dichotomise continuous variables such as skeletal age and percentage of predicted adult height, although this facilitates comparisons and illustrations between different maturity groups. Instead, more sophisticated data analysis techniques such as linear regression techniques are recommended to employ which do not violate statistical assumptions while achieving the desired outcome (Altman & Royston, 2006; Prince Nelson et al., 2017).

Similar to previous research, findings of Chapter 4 indicate a maturity-related selection bias towards biologically more advanced athletes. This trend started to emerge in the U14 age group coinciding with start of puberty and remained relatively constant through to the U17 age group. These findings fit well in the current body of research of male youth players aged 11 to 17 years (Hirose, 2009; Johnson et al., 2017; Malina, Chamorro, et al., 2007; Malina et al., 2010). While early maturing athletes are over proportionally selected or remain within the high-performance program, late maturing athletes are de-selected or drop out, likely primarily due to anthropometrical and physical performance disadvantages (Figueiredo et al., 2009a). Despite the underrepresentation of late maturing athletes, there was also a large inter-individual variability in skeletal age across all age groups. Differences of up to 4.5 years should be expected within U14 to U17 age groups (Johnson et al., 2017). This presents several challenges for practitioners of those age groups, particularly when prescribing and assessing maturity-specific training load and responses to load, respectively.

8.1.2 How reliable are measurement instruments to assess acute responses to load?

Reliability is an important measurement property when evaluating the usefulness of a measurement instrument. It refers to the extent to which the scores of a parameter for athletes who have not changed are the same for repeated measurement under several conditions (Mokkink et al., 2010; Streiner et al., 2015). One critical statistical estimate for practitioners is the smallest detectable change (SDC), which is the smallest change that can be detected beyond measurement error (including normal biological variation) (Vet et al., 2011). Previous research often used pre-determined and arbitrary thresholds such as <10% for the typical error of measurement, expressed as coefficient of variability to decide whether a parameter can be considered as reliable (Aben et al., 2020; Cormack, Newton, McGuigan, et al., 2008; Roe et al., 2016). The SDC can be considered as a more stringent estimate as it constructs a confidence level around the measurement error. Practitioners can also select the confidence level (e.g., 75%, 90% or 95%) they perceive as acceptable according to their environment. Changes exceeding the SDC can therefore be considered as ‘real’ (Buchheit, 2014; Haugen & Buchheit, 2016). Findings from Chapter 5 provide maturity-specific reference values for the SDC for commonly used measurement instruments such as the SRSS as athlete-reported questionnaire and CMJ, submaximal hopping, and a submaximal run as performance-based measurements. These data are specific to the investigated population, i.e., youth soccer players of varying maturity status ranging from pre-PHV to post-PHV. Collectively, items of both the recovery and stress scale of the SRSS (SDC of ~1 AU for the pre-PHV group, ~1 to 2 AU for the at-PHV group, and ~2 for the post-PHV group) showed relatively poor short-term reliability. Similarly, only a few parameters of the CMJ and HRex from the submaximal run showed small day-to-day variability across all maturity groups. Interestingly, there was an inverse trend for the parameter of the CMJ and sub-maximal hopping test, whereby better reliability statistics were observed in the post-PHV followed by at-PHV and pre-PHV group. This is in accordance with previous research examining the reliability of vertical and horizontal jumps in relation to the biological maturity status (Meylan et al., 2012). Clearly, maturity impacts the normal variation in measurements (i.e., within-athlete day-to-day variability), which has to be taken into consideration when evaluating changes within age groups of athletes with large inter-individual variation in biological maturity. While a certain change score might be considered as real and thus concerning for a post-PHV player and requires adjustment of the training program, the same change score is well within the day-to-day variability of a pre-PHV player.

Importantly, it is not the absolute magnitude of the SDC of a given parameter that matters, but the magnitude of this 'noise' in relation to i) the typically observed acute and chronic responses to load and ii) the minimal important change (MIC), i.e., the smallest change which can be considered as practically important for the athlete (Buchheit, 2014; Mokkink et al., 2010). A parameter with a relatively small SDC, but even smaller acute and chronic responses to load might be considered as less useful than a parameter with a relatively large SDC, but even greater acute and chronic responses to load (Buchheit, 2014; Haugen & Buchheit, 2016; Ryan et al., 2019). While the MIC requires separate discussion and scientific evaluation, information about the responsiveness provides important and worthwhile information to critically appraise and establish the usefulness of a given parameter (Fitzpatrick et al., 2019). Nevertheless, findings from Chapter 5 highlight that relatively large acute and chronic changes would be required to detect meaningful psycho-physiological responses to load that are beyond the measurement error in youth soccer players irrespective of the maturity status.

8.1.3 How responsive are measurement instruments to assess acute responses to load during regular and intensified periods?

Another important measurement property when evaluating the usefulness of a measurement instrument is responsiveness. It refers to the ability of a given parameter to detect changes in the construct of interest (Mokkink et al., 2010). Assessing responsiveness in the applied setting is challenging (see section 8.2.4 below), potentially explaining the relatively paucity of studies examining acute and chronic responses to load in youth soccer players. Findings from Chapter 6 and 7 provide therefore valuable information about the observed responses during regular (i.e., in-season) and intensified (i.e., pre-season training camp) training periods of U15 soccer players. During in-season periods focus often shifts towards the technical and tactical preparation for the upcoming match with periodisation across the weekly micro-cycle (i.e., increased training load in the middle and decreased training load at the end of the week) being only apparent in the older age groups (Hannon, Coleman, et al., 2021). Results from Chapter 6 investigating the responsiveness after two days of load accumulation during the in-season indicated that i) magnitudes of changes in all items for athlete-reported rating of recovery and stress from the SRSS were only trivial to small and smaller than the typically observed day-to-day variability, ii) changes in all CMJ parameters were only trivial to small not exceeding the day-to-day variability, and iii) only changes in HRex were moderate and larger than the typically observed day-to-day variability. Collectively, these findings highlight the generally poor responsiveness of most parameters questioning the usefulness to monitor psycho-physiological responses to regular in-season training sessions in U15 adolescent soccer players. Similar findings have been recently reported in U13 to U16 soccer players whereby only trivial to small changes were observed following a simulated soccer-specific activity (Salter, Croix, & Hughes, 2021). Of note, however, it cannot be ruled out that either the training load during this in-season period was not high enough to elicit substantial psycho-physiological responses or the unique physiological and psychological make up of adolescent athletes generally reduces the exercise-induced changes to load (Ratel & Martin, 2015; Ratel & Williams, 2017) and in turn reduces the responsiveness. Thus, Chapter 7 examined the responsiveness of the same measurement instruments to a typical pre-season period including a short training camp of increased training load. Findings of Chapter 7 indicated that changes in CMJ parameters were smaller than the day-to-day variability and did not follow the temporal changes in training load. In contrast, both athlete-reported items related to the Physical Performance Capability, Emotional Balance and Overall Recovery as well as Muscular Stress and Overall Stress of the SRSS and HRex fluctuated moderately in temporal relation to changes in training load during the camp. Changes were also larger than the typically observed day-to-day variability, thus representing indicators to help making informed decisions if adjusting the training plan is required or programming can continue as planned. Despite its popularity in practice (Taylor et al., 2012), the various parameter reflecting the kinetics and kinematics of the CMJ might not provide valuable insight into neuromuscular responses to load in U15 soccer players, irrespective of the training phase and in turn short-term accumulated training load. Similar (Norris et al., 2021) and contradictory findings (Gathercole et al., 2015) have been recently reported in senior professional team sport athletes highlighting the complexity (i.e., differences in accumulated training load, timing of measurements, physical fitness of athletes, etc.) in interpreting the usefulness of the CMJ as a practical measurement instrument to monitor acute responses to load.

Interpreting these findings in conjunction with the previous findings about the reliability (see Chapter 5), the usefulness of every parameter can be determined. Based on this holistic evaluation, only few parameters might be worthwhile to implement within the athlete monitoring process. Overall, HRex as derived from a submaximal run provides a reliable and responsive parameter to monitor acute cardiovascular responses to load during regular in-season and intensified pre-season periods. Although athlete-reported measurement instruments relying on subjective perceptions might be interpreted with caution within adolescent populations (Kölling et al., 2019), the SRSS might provide a valuable measurement instrument, particularly during intensified periods to monitor several constructs (i.e., recovery and stress) and domains (i.e., Physical Performance Capability, Emotional Balance, Overall Recovery, Muscular Stress, and Overall Stress) that are not objectively measurable (McLaren et al., 2021). Parameters derived from the CMJ, however, add little additional value during regular and intensified periods of training load, thus providing limited usefulness within the athlete monitoring framework.

8.2 Methodological considerations

Although this thesis contributed from a theoretical and practical perspective to the already existing body of research, several methodological considerations including limitations need to be acknowledged when interpreting the findings. Most of these methodological considerations are a product arising from the applied setting in which the included studies were conducted.

8.2.1 Participants and academy context

Findings of each scientific study is specific to the population under investigation and should be considered when interpreting our findings. Participants of Study I, III and IV belonged to one youth academy of a professional soccer club in Germany. This ultimately reduces the generalisability of our findings to other contexts such as other clubs at different countries following different strategies with regards to talent identification and selection as well as training content and delivery. Similarly, for Studies III and IV were only recruited with the U15 only one single age group, which prevents the extrapolation of our findings to other age groups. This represents a limitation of both studies as youth players of younger and older age possess an unique set of growth, maturity and, physical characteristics (Beunen & Malina, 2007; Ratel & Williams, 2017) likely influencing the magnitude of acute responses to a given stimulus thus impacting the responsiveness of those measurement instruments. Our findings are therefore only applicable to this age group and to players with similar training background greatly reducing the external validity.

8.2.2 Biological maturation assessments

A standard radiograph of the hand-wrist is an established clinical indicator of skeletal maturity as the skeletal age of a player can be determined from it. However, the assessment of skeletal age based on a standard radiograph of the hand-wrist is associated with several limitations such as the lack of qualified personnel to take radiographs and interpret them according to the respective method, logistical constraints for individuals associated with the assessment, expenses associated with the radiographs, and exposure to minimal radiation (Malina et al., 2015). Given these limitations, we were unable to include standard radiographs as an indicator of skeletal maturity in Study I (Chapter 4). This would have allowed to assess the criterion validity of the BAUS™ system against established protocols of skeletal age derived from a standard radiograph such as the Tanner-Whitehouse (TW1, TW2, and TW) (Tanner et al., 1975, 1983, 2001) and Fels (Roche et al., 1988) method. Instead, we used a construct validity approach by comparing percentage of predicted adult height (i.e., an indicator of somatic maturity) against skeletal age (i.e., an indicator of skeletal maturity), which likely reduces the robustness of our findings. In addition, while it would have been desirable to assess biological maturation with the same protocol throughout the subsequent Studies II, III, and IV (Chapter 5, 6, and 7), it was not feasible to align the protocols used within the different youth academies involved in those studies. However, it can be argued that the variety of protocols used represents realistic scenarios in practical settings across high-performance environments according to their available resources. Lastly, ethnic variation and differences in the study samples and reference samples that were used to develop the Khamis-Roche method (Khamis & Roche, 1994) which was the basis for the calculation of percentage of predicted adult height and skeletal age as derived from the BAUS™ system need to be considered. As such, players might have been categorised in a wrong maturity band in Study II potentially impacting the reliability of certain measurement instruments, although it is unlikely that there was a systematic bias associated with the applied protocol of percentage of predicted adult height.

8.2.3 Training load indicators

Training load is a high-order construct that accommodates a variety of measures from the spatio-temporal, mechanical, psychological, and physiological domain to reflect what an athlete actually does or experiences during activity. We used total distance and high-speed running distance as indicators reflecting the external training load construct, and sRPE-TL as an indicator reflecting the internal training load construct. Despite a plethora of indicators being available, those three indicators are most commonly used in practice of high-performance programs (Akenhead & Nassis, 2016). Their wide spread adoption might be explained by the fact that they are valid, reliable, and simple enough to be understood and in turn manipulated by practitioners and coaches (Buchheit & Simpson, 2017). Total distance is considered to reflect the overall training volume of a player. High-speed running distance is supposed to reflect more the neuromuscular-oriented training volume. Yet, it is unknown to infer from those indicators on the underpinning physiological (e.g., metabolic energy cost) and mechanical (e.g., tissue stress and strain, muscle-tendon forces) demands the musculoskeletal system experiences during exercise (i.e., muscles, tendons, ligaments, bones). While several indicators reflecting the whole-body mechanical loads exists (e.g., Dynamic Stress Load (Gaudino et al., 2015), Player Load™ (Barrett et al., 2014)), they are unable to adequately quantify the loads acting on the tissue level with the ability to directly or indirectly measure mechanical loads being primarily limited to a lab context (Verheul et al., 2020). This is problematic as a solid foundation is lacking as to what physiological and mechanical systems currently used external spatio-temporal training load indicators measure. Similarly, as athlete-reported ratings of perceived exertion (e.g., sRPE) is a post-hoc appraisal of effort experienced during a training session or match and therefore reflects a single, gestalt measure of intensity which ultimately makes it impossible to decipher the underpinning physiological and mechanical origin of the perception. No note, the differential RPE (dRPE) as a variation of sRPE has been developed by separating the global sRPE into central (e.g., breathlessness) and peripheral (e.g., leg muscle) exertion to overcome this limitation, however, the limitation pertaining the underpinning physiological and mechanical load pathways remains. A major limitation of this thesis is therefore that no a priori clear physiological and mechanical causal pathway between the external and internal training load indicators and acute response measurement instruments could be established, but rather training load indicators and measurement instruments were selected based on current best practice within soccer high-performance programs. This would have been desirable as it allows to monitor specific aspects of interest of the physiological and mechanical system and select the most appropriate measurement instruments to quantify the subsequent acute response for the respective system. Such approach allows to investigate specific associations of the conceptual framework underpinned by a causal physiological and mechanical foundation. The research included in this thesis can therefore be interpreted as explorative in nature highlighting and questioning currently adopted training load indicators within practice and research.

8.2.4 Evaluating responsiveness of measurement instruments

Papers III and IV aimed to examine the responsiveness of commonly used measurement instruments to monitor acute psycho-physiological responses to load in youth soccer during regular training weeks and a pre-season camp. To evaluate responsiveness both studies followed a construct-based approach whereby it was assumed that changes in the selected measurement instruments fluctuate in relation to accumulated training load as depicted in the conceptual framework (see Figure 2.1). To do so repeated-measures after substantial and practically relevant contrasting time points (i.e., after a period of accumulated training load vs after a period of no or reduced training load) during habitual training weeks are required. There should be then a clear dose-response relationship with the stronger the relationship between both constructs, i.e., accumulated load and acute responses and, the greater the responsiveness for the given measurement instrument. This approach represents a major limitation in the design of Study III and IV. In the absence of a criterion measurement instrument, it can not clearly determined whether i) external or internal training load was not high enough to actually elicit substantial impairments in psycho-physiological responses, ii) training load indicators are not able to adequately quantify the relevant information of the training load construct, or iii) the selected measurement instruments simply lack responsiveness. Thus, a lack of substantial change in a measurement instrument might be the consequence of one or a combination of several of these points preventing us to draw clear conclusions regarding the responsiveness for this given parameter. The lack of standardisation of the training sessions and in turn training load as well as the limited control of individual and contextual factors further exacerbates the difficulty when interpreting our findings. Nevertheless, due to the applied nature of the data collection both studies reflect the real-world practice within youth soccer academies and can therefore be characterised as effectiveness studies. While such studies have greater external validity given the close proximity to the real world conditions, this comes at the expense of several potential sources of error and factors outside our control may be partially responsible for the results, ultimately reducing the internal validity (Singal et al., 2014). While this does not discard the usefulness of the approach taken and the resulting findings, it is important to appropriately acknowledge the potential shortcomings with this type of research. Consequently, a series studies spanning the continuum from effectiveness (i.e., more closely resemble real-world practice) to efficacy (i.e., more closely resemble ideal circumstances) are required to fully evaluate the responsiveness of those measurement instruments in youth soccer (Streiner, 2002).

These above mentioned aspects should be recognised as a starting point for future research projects to plan and conduct more robust and rigorous study designs providing a stronger evidence base for practitioners aiming to monitor acute psycho-physiological responses to load to maximise performance and health of youth soccer players.

8.3 Recommendations for future research

Building on these methodological considerations described in the previous section containing several limitations associated with the body of this thesis, future research should aim to conduct more controlled and standardised studies by addressing the following aspects outlined in this section.

While difficult and at times impossible to conduct in youth high-performance programs given the high-pressures environment, research should strive towards conducting efficacy studies within the area of monitoring acute and chronic psycho-physiological responses to load. The recent advancements in technology enabled practitioners to monitor various aspects of the training process including external and internal loads during training sessions and matches as well as acute and chronic responses to load. As a result, there was a great interest from the scientific community to describe the daily, weekly, and monthly training loads as well as the subsequent responses to these loads players experience across all age groups and playing standards. Most of these studies including the studies of this thesis were, however, observational in nature limiting the relative strength of the results obtained from these scientific studies. Observational studies may help to generate new hypotheses given their greater proximity to real life scenarios. However, there is a general lack of control associated with this study design adding a lot of unexplained variability and uncertainty to the findings. There is a myriad of individual and contextual modifiable factors (e.g., sleep behaviour, medication, ergogenic aids, social influences, and commercial responsibilities) potentially influencing how athletes respond to a given stimulus. It is therefore important to firstly acknowledge these mediating and moderating factors and ideally measure and control for as many as possible to reduce the magnitude of noise within the signal. A possible solution from a methodological standpoint to this problem might be to perform more controlled experiments either in the real-world or laboratory setting. Simulated soccer matches or standardised training sessions including standardised drills such as sided-games (Dello Iacono et al., 2022) to emphasis specific spatial-temporal profiles (i.e., emphasis on acceleration, deceleration and change of direction vs high-speed running and sprinting) might therefore provide viable options to design crossover studies which in turn allows to elucidate the responsiveness of measurement instruments to distinct physical profiles in a more controlled fashion. Alternatively, the laboratory setting allows for an even greater control of the type and magnitude of the stimulus and subsequent time period while also offering the inclusion of more sophisticated measurement instruments to investigate the underpinning mechanisms of the acute responses from a mechanistic perspective. While appealing at first, this approach lacks ecological validity and is likely not feasible to conduct within high-level youth soccer given their weekly training and match schedule. Nevertheless, such studies might be of great value in the area of monitoring acute psycho-physiological responses to load as they might allow the detailed investigation of several hypothesised associations of the conceptual framework while teasing out the potential impact of individual and contextual factors in these associations.

This thesis has investigated the responsiveness of commonly used measurement instruments within U15 soccer players. Although there is a great variability in terms of biological maturity within this age group with players ranging from pre- to post-pubertal status, we were unable to include players from other age groups which in turn would have allowed to explicitly investigate the moderating impact of biological maturity upon the responsiveness of the included measurement instruments. Future research might therefore aim to determine the responsiveness across the entire adolescence, i.e., including pre-, circa- and post-pubertal players to elucidate how they of might respond differently to a given stimulus. Preliminary research suggests that there might be a small moderating effect of biological maturation to the experienced internal training load (i.e., sRPE-TL) to a standardised simulated soccer match of players from the U13 to U16 age group (Salter, Croix, & Hughes, 2021). More work is needed to corroborate these findings by including measurement instruments targeted to the expected psycho-physiological responses after the training load stimulus while also including other age groups.

This thesis also provided an overview of the inherent variability of a range of measurement instruments commonly used in high-performance programs. The calculation of the measurement error is a crucial statistic from which the SDC can be derived. This threshold implies the change required in a parameter to exceed the typical day-to-day variability at a given confidence level. Another important statistic to consider alongside the SDC is the minimal important change (MIC) (Vet et al., 2011). The MIC describes the smallest change in score in the construct to be measured which can be considered as practically important for the athlete (Mokkink et al., 2010). However, care should be taken as MICs may be unreliable and dependent on the baseline score resulting in only conditionally valid MICs (Boyer et al., 2022). In addition, to date, there is a paucity of validated athlete-reported questionnaires that can be used as an anchor to calculate the MICs for each parameter (Jeffries et al., 2020). Nevertheless, to fully evaluate the usefulness of each measurement instrument it is necessary to interpret the actual change score in relation to the SDC and MIC. Therefore, future research might look into determining the MIC for various measurement instruments in youth athletes of different biological maturity.

From a methodological perspective evaluating the responsiveness of measurement instruments aiming to monitor acute psycho-physiological responses to load as a measurement property is challenging. There is and likely will never be a single gold standard measurement instrument that is able to capture the complex, interrelated, and multifaceted nature of psycho-physiological responses to load. Given the lack of a criterion measurement instrument a criterion validity approach can not be applied and instead a construct validity approach needs to be adopted. Following this line of thought, it is critical to firstly outline what physiological, mechanical, or spatio-temporal measures are most important to monitor for a given athlete and sport from both a training load and response to load construct to inform subsequent training prescription. Although our external (i.e., total distance, high-speed running distance) and internal training load indicators (i.e., sRPE-TL) are commonly used in the applied setting (Nosek et al., 2021), it is likely that these indicators do not accurately estimate the actual physiological and mechanical demands of the training load construct (Vanrenterghem et al., 2017). Research might therefore develop and evaluate training load indicators that provide deeper insight into the actual mechanical demands of the training load construct. Similarly, the current measurement instruments might not be able to adequately capture the underlying systems supposed to be influenced by the preceding stimulus. For example, kinematic and kinetic variables derived from a CMJ are supposed to be reflective of changes of the neuromuscular system (Gathercole et al., 2015). While some recent findings including our work seem to support the notion that kinetic and kinematic parameters of the eccentric phase of a CMJ might fluctuate in response to accumulated training load (Mercer et al., 2022), the magnitude of those associations was small highlighting the complexity of the neuromuscular system with a lot of variability left unexplained. In addition, little is known about the actual etiology (i.e., contractile function, muscle activation (Enoka & Duchateau, 2016)) if an athlete has impaired kinetic and kinematic variables in a CMJ, if the underpinning mechanisms are consistent and how these mechanism translate to sport-specific movements. Future research might therefore aim to measure various aspects of the entire spectrum of the neuromuscular system ranging from isolated (e.g., twitch responses to electrical stimulation) to integrated measurement instruments (e.g., CMJ) to sport-specific movements (e.g., linear sprint) in order to better understand the origin and relevance of substantial neuromuscular responses to load. Similarly, further refinement and development of existing and new measurement instruments specifically targeting certain aspects of the neuromuscular system might enable practitioners to further break down the complexity of the neuromuscular system by manipulating one specific aspect of interest.

Finally, from a conceptual perspective, this thesis only investigated a small aspect of the entire training process, namely the association between the constructs of training load and acute responses to load. Several individual and contextual factors potentially influencing these associations were not measured and therefore formally investigated. In this context, biological maturity might play a key role given the large inter-individual variability within youth soccer acting as a moderating factor in this relationship and further research might identify their role within the training process. Similarly, all other associations of the training process deserve formal investigation such as the association between training load and chronic responses and their link to the actual sports performance outcomes. This ultimately allows practitioners to better understand which measurement instruments are worthwhile implementing in their daily practice and why they are important.

8.4 Practical applications for implementing an athlete monitoring framework in a high-level youth soccer environment

Monitoring the youth soccer player is now considered as a central component within high-performance programs. Coaches and practitioners typically value this process as it evaluates and guides the effectiveness as well as facilitates the prescription and manipulation of training load and recovery strategies. Practitioners are faced with the challenge in selecting the most appropriate measurement instruments to monitor the aspects within the constructs of training load and responses to load that are more relevant and required to adjust the training plan. Considerations should be given to theoretical and contextual aspects such as scalability to large groups of athletes, time efficiency, cost-effectiveness as well as to the scientific evaluation of the measurement properties of reliability, validity, and responsiveness.

A key practical application of this thesis relates therefore to the findings around the inherent variability of measurement instruments practitioners need to consider in relation to the biological maturity of an athlete in order to detect changes that are beyond the measurement error for a given parameter. For example, the SDC for HRex for a post-pubertal athlete is 6.6 beats per minute (90% confidence interval 5.7 to 7.7 beats per minute), this stipulates that a change greater than 7 beats per minute is required to be considered beyond measurement error and therefore real at a 90% confidence level. This enables practitioners to determine if changes in response to load are progressing as initially intended or if the training plan requires small adjustments. For example, a negative response beyond measurement error in one or several parameters that is planned (e.g., during an intensified period such as pre-season) might not represent a call for action. However, in case of an unplanned negative response beyond measurement error (e.g., during a period of reduced training and match load), this may prompt further investigation into contextual and individual factors, modulate external training load, or provide additional recovery strategies to avoid maladaptation. Therefore, information about the SDC for each parameter enables practitioners to accurately interpret acute responses to load and adequately inform subsequent training sessions to optimise the training process. Despite only small differences, practitioners also need to consider the biological maturity of each player when interpreting acute psycho-physiological responses to load. For example, while a change of 100 ms in eccentric duration during a CMJ for a post-pubertal athlete (SDC: 55 ms) might warrant an intervention, a change of similar magnitude for a pre-pubertal athlete might be interpreted as measurement error (SDC: 169 ms) with the training plan proceeding as planned.

Another key practical application of this thesis relates to the findings around the evaluation of the responsiveness. Our findings suggest that during a regular in-season period in U15 soccer players, acute responses to load for athlete-reported items of the SRSS and CMJ barely exceeded the measurement error after a short period of accumulated training load. This calls into question the necessity to adapt an athlete monitoring system within this age group (i.e., U15) and non-intensified periods (i.e., in-season). However, during periods of increased training load (e.g., pre-season training camps), athlete-reported parameters such as items related to the Physical Performance Capability, Emotional Balance and Overall Recovery as well as Muscular Stress and Overall Stress of the SRSS may provide valuable insights into the constructs of recovery and stress within this age group. Similarly, a sub-maximal run to assess heart rate responses showed promise to monitor cardiorespiratory responses to load during periods of regular and increased training load acting as a simple, cost-effective, and non-invasive measurement instrument that can easily be implemented in a training session as part of a warm-up. However, changes in HRex need to be contextualised as acute negative and chronic positive cardiorespiratory changes follow the same pattern. Parameters derived from force-time data of a CMJ seem to add limited value to monitor aspects of the neuromuscular system despite their popularity and widespread adoption within high-performance programs.

Finally, there are several key points practitioners need to consider when aiming to develop a or revise their athlete monitoring system. The proposed conceptual framework may assist practitioners to identify the constructs that are most relevant for their specific context and therefore worth monitoring and manipulating. Formulating the target construct and assumptions one is making may help practitioners to avoid post hoc justification as to why a given measurement instrument was implemented. Practitioners and coaches should therefore precisely decide what information is required and why it can help to optimise the training process. For example, the constructs of fatigue and recovery might be considered as most important. Accumulating training while being excessively fatigued might compromise physical and physiological adaptations. Measurement instruments quantifying components of the constructs of fatigue and recovery may therefore be viewed as critical to evaluate previous and adjust or plan future training sessions. Once the target constructs are defined all available measurement instruments should be extracted from the literature and evaluated according to the measurement properties. In addition, several other aspects such as possible barriers and challenges with the application of the measurement instrument to the specific athlete group need to be considered and reflected upon. Finally, the last step is the selection of the most appropriate measurement instrument.

8.5 Conclusions

Based on the findings of this thesis that evaluated the reliability and responsiveness of commonly used measurement instruments to assess acute psycho-physiological responses to load of youth soccer players, several key points can be concluded from a theoretical, methodological, and conceptual perspective.

Firstly, this thesis provides benchmark information on measurement variability and changes that are beyond the instrumentation and biological noises for commonly used measurement instruments within high-performance programs in youth soccer. Most of the included parameters possess poor short-term between-days reliability irrespective of the maturity status. To fully evaluate the usefulness of a measurement instrument information about the inherent variability of a parameter need to be complemented with information about the typical observed changes to normal and intensified periods of training. Our results suggest that the majority of investigated measurement instruments to assess acute psycho-physiological responses have limited short-term responsiveness to a short-period of accumulated training load during the in-season. During intensified periods of increased training load such as a training camp, the athlete-reported recovery and stress scales of the SRSS and heart rate responses during the sub-maximal run showed small to moderate changes in temporal relation to fluctuations in training load and might therefore be useful measurement instruments within the athlete monitoring process for adolescent soccer players. Parameters derived from the force-time data of a CMJ might however provide little insight into acute neuromuscular responses to load.

Secondly, this thesis highlighted several methodological considerations and limitations associated with the applied nature of the included studies. This relates in particular to the training load indicators and measurement instruments adopted to operationalise the constructs of training load and acute responses to load and hence the reliability and responsiveness of the respective parameters. Currently implemented measurement instruments to quantify training load and acute responses are primarily adopted given their availability, practicality, and ease to administer to large groups while limiting player physical and mental exertion. Consequently, this approach limits the insight gained into the underpinning physiological and mechanical demands and associated responses. Coupled with the multitude of individual and contextual factors impacting the results of such applied research and effectiveness studies, the robustness of the findings of this thesis might be compromised. Further refinement and development of training load indicators and measurement instruments is needed to better understand the actual physiological and mechanical aspects of training load and acute responses and allows practitioners to select and specify their monitoring approach to the key areas of interest. This would also enable practitioners to design and conduct high quality research with a greater degree of control around the association between training load and responses to load while controlling for contextual and individual factors.

Thirdly, this thesis investigated a small aspect of the conceptual framework of monitoring the youth soccer player, namely the association between both constructs of training load and acute responses. Such a framework may help to understand and guide the monitoring process from a practical perspective while informing future research in evaluating the proposed associations. While the link between training load and acute psycho-physiological responses appears to be small to moderate at best for the investigated measurement instruments, little high-quality research is available assessing the impact of individual and contextual factors acting as potential moderator or mediator in the association between training load and response to load. Biological maturity might play a crucial role in this context given its close link to the physical development of a youth athlete. Understanding maturity-specific psycho-physiological responses to a given stimulus enables practitioners to individualise the prescription of activities that are high in mechanical loading (e.g., accelerations, decelerations, changes of direction) in an attempt to reduce injury incidence of growth-related injuries particularly for athletes approaching and experiencing their growth spurt. Conceptionally, further evaluation of the proposed framework and its associations is required to optimise health and performance of the adolescent soccer player.

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Chapter 10: Appendices

10.1 Appendix A: Ethical approvals

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Datum 2.5.2019
Betreff Ethik-Antrag

Sehr geehrte Frau Dr. Skorski,

die Ethikkommission der Fakultät für Empirische Humanwissenschaften und Wirtschaftswissenschaft der Universität des Saarlandes hat Ihren Antrag 19-06 „Reliabilität und Sensitivität von Parametern zur Quantifizierung des akuten Ermüdungszustandes bei Nachwuchsfußballspielern" begutachtet und entschieden, ihn mit einer nur kleinen Auflage zu genehmigen: Bitte beachten Sie die Unterscheidung zwischen Anonymisierung und Pseudonymisierung, wie sie im beigelegten Informationsblatt erklärt wird.

Freundliche Grüße,

Cornelius König

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Datum 26.5.2020

Betreff **Ethik-Antrag**

Sehr geehrter Herr Ruf,

die Ethikkommission der Fakultät für Empirische Humanwissenschaften und Wirtschaftswissenschaft der Universität des Saarlandes hat Ihren Antrag 20-18 „Untersuchung der Trainingsbelastung sowie Ermüdungsreaktion mit besonderer Bezugnahme auf die biologische Reife im Nachwuchsfußball" begutachtet und entschieden, ihn ohne Auflagen zu genehmigen.

Freundliche Grüße,

Cornelius König

10.2 Appendix B: Supplementary files from publications incorporated into this thesis

10.2.1 Chapter 4: Construct validity of percentage of predicted adult height and BAUS skeletal age to assess biological maturity in academy soccer

Supplementary Table 10.1. Crosstabulation of maturity status classifications based on z-scores for percentage of predicted adult height and absolute differences between skeletal age (SA) and chronological age (CA) in the U12 (n = 18).

		Maturity status based on SA-CA difference				Agreement		
cut-off z-score	**Maturity status based on percentage of predicted adult height**	**Late**	**On-time**	**Early**	**Total**	**Percent agreement (95% CL)**	**Kappa κ (95% CL)**	**Spearman rank-order correlation (95% CL)**
z = 0.50	Late	1	1	0	2	61% (36 to 82)	0.30 (0.00 to 0.65)	0.52 (0.16 to 0.78)
	On-time	2	8	4	14			
	Early	0	0	2	2			
	Total	3	9	6	18			
z = 0.75	Late	1	1	0	2	72% (46 to 89)	0.32 (0.00 to 0.78)	0.45 (-0.05 to 0.82)
	On-time	1	11	2	14			
	Early	0	1	1	2			
	Total	2	13	3	18			
z = 1.00	Late	0	2	0	2	72% (49 to 90)	0.23 (0.00 to 0.79)	0.30 (-0.11 to 0.73)
	On-time	1	12	1	14			
	Early	0	1	1	2			
	Total	1	15	2	18			

Supplementary Table 10.2. Crosstabulation of maturity status classifications based on z-scores for percentage of predicted adult height and absolute differences between skeletal age (SA) and chronological age (CA) in the U13 (n = 15).

		Maturity status based on SA-CA difference				**Agreement**		
cut-off z-score	**Maturity status based on percentage of predicted adult height**	**Late**	**On-time**	**Early**	**Total**	**Percent agreement (95% CL)**	**Kappa κ (95% CL)**	**Spearman rank-order correlation (95% CL)**
z = 0.50	Late	1	1	0	2	60% (33 to 83)	0.30 (0.00 to 0.72)	0.52 (0.04 to 0.83)
	On-time	3	6	1	10			
	Early	0	1	2	3			
	Total	4	8	3	15			
z = 0.75	Late	1	1	0	2	73% (45 to 91)	0.46 (0.02 to 0.91)	0.60 (0.04 to 0.91)
	On-time	1	8	1	10			
	Early	0	1	2	3			
	Total	2	10	3	15			
z = 1.00	Late	1	1	0	2	80% (51 to 95)	0.50 (0.05 to 0.95)	0.63 (0.37 to 1.00)
	On-time	0	10	0	10			
	Early	0	2	1	3			
	Total	1	13	1	15			

Supplementary Table 10.3. Crosstabulation of maturity status classifications based on z-scores for percentage of predicted adult height and absolute differences between skeletal age (SA) and chronological age (CA) in the U14 (n = 17).

		Maturity status based on SA-CA difference				Agreement		
cut-off z-score	**Maturity status based on percentage of predicted adult height**	**Late**	**On-time**	**Early**	**Total**	**Percent agreement (95% CL)**	**Kappa κ (95% CL)**	**Spearman rank-order correlation (95% CL)**
z = 0.50	Late	0	0	0	0	82%	0.64	0.65
	On-time	0	6	2	8	(56 to 95)	(0.28 to 1.00)	(0.24 to 1.00)
	Early	0	1	8	9			
	Total	0	7	10	17			
z = 0.75	Late	0	0	0	0	82%	0.46	0.65
	On-time	0	7	1	8	(45 to 91)	(0.02 to 0.91)	(0.25 to 1.00)
	Early	0	2	7	9			
	Total	0	9	8	17			
z = 1.00	Late	0	0	0	0	88%	0.77	0.79
	On-time	0	8	0	8	(62 to 98)	(0.47 to 1.00)	(0.52 to 1.00)
	Early	0	2	7	9			
	Total	0	10	7	17			

Supplementary Table 10.4. Crosstabulation of maturity status classifications based on z-scores for percentage of predicted adult height and absolute differences between skeletal age (SA) and chronological age (CA) in the U15 (n = 20).

		Maturity status based on SA-CA difference				Agreement		
cut-off z-score	**Maturity status based on percentage of predicted adult height**	**Late**	**On-time**	**Early**	**Total**	**Percent agreement (95% CL)**	**Kappa κ (95% CL)**	**Spearman rank-order correlation (95% CL)**
z = 0.50	Late	0	0	0	0	70%	0.46	0.71
	On-time	2	6	0	8	(46 to 87)	(0.15 to 0.78)	(0.49 to 0.90)
	Early	0	4	8	12			
	Total	2	10	8	20			
z = 0.75	Late	0	0	0	0	60%	0.29	0.41
	On-time	0	8	0	8	(36 to 80)	(0.02 to 0.55)	(0.19 to 0.65)
	Early	0	8	4	12			
	Total	0	16	4	20			
z = 1.00	Late	0	0	0	0	55%	0.21	0.34
	On-time	0	8	0	8	(32 to 76)	(0.00 to 0.44)	(0.17 to 0.58)
	Early	0	9	3	12			
	Total	0	17	3	0			

Supplementary Table 10.5. Crosstabulation of maturity status classifications based on z-scores for percentage of predicted adult height and absolute differences between skeletal age (SA) and chronological age (CA) in the U16 (n = 22).

		Maturity status based on SA-CA difference				Agreement		
cut-off z-score	**Maturity status based on percentage of predicted adult height**	**Late**	**On-time**	**Early**	**Total**	**Percent agreement (95% CL)**	**Kappa κ (95% CL)**	**Spearman rank-order correlation (95% CL)**
z = 0.50	Late	0	0	0	0	77% (54 to 91)	0.40 (0.00 to 0.83)	0.40 (-0.13 to 0.81)
	On-time	0	3	3	6			
	Early	0	2	14	16			
	Total	0	5	17	22			
z = 0.75	Late	0	0	0	0	50% (29 to 71)	0.14 (0.00 to 0.42)	0.20 (-0.21 to 0.52)
	On-time	0	5	1	6			
	Early	0	10	6	16			
	Total	0	15	7	22			
z = 1.00	Late	0	0	0	0	41% (21 to 63)	0.11 (0.00 to 0.25)	0.24 (0.10 to 0.42)
	On-time	0	6	0	6			
	Early	0	13	3	16			
	Total	0	19	3	22			

Supplementary Table 10.6. Crosstabulation of maturity status classifications based on z-scores for percentage of predicted adult height and absolute differences between skeletal age (SA) and chronological age (CA) in the U17 (n = 22).

		Maturity status based on SA-CA difference				Agreement		
cut-off z-score	**Maturity status based on percentage of predicted adult height**	**Late**	**On-time**	**Early**	**Total**	**Percent agreement (95% CL)**	**Kappa κ (95% CL)**	**Spearman rank-order correlation (95% CL)**
z = 0.50	Late	0	1	0	1	na	na	0.05 (-0.41 to 0.48)
	On-time	0	5	9	14			
	Early	0	3	4	7			
	Total	0	9	13	22			
z = 0.75	Late	0	1	0	1	77% (54 to 91)	0.44 (0.09 to 0.80)	0.56 (0.31 to 0.84)
	On-time	0	14	0	14			
	Early	0	4	3	7			
	Total	0	19	3	7			
z = 1.00	Late	0	1	0	1	68% (45 to 85)	0.16 (0.00 to 0.44)	0.31 (0.22 to 0.61)
	On-time	0	14	0	14			
	Early	0	6	1	7			
	Total	0	21	1	22			

Supplementary Table 10.7. Pearson's correlation coefficients between skeletal age derived from the BAUS system and percentage of predicted adult height derived from the Khamis-Roche method relative to all age groups.

Age group	Sample size	Correlation coefficient (95% CL)
U12	18	0.50 (0.04 to 0.78)
U13	15	0.55 (0.06 to 0.83)
U14	17	0.76 (0.44 to 0.91)
U15	20	0.76 (0.47 to 0.90)
U16	22	0.75 (0.49 to 0.89)
U17	22	0.01 (-0.42 to 0.43)
Total	114	0.94 (0.91 to 0.96)

10.2.2 Chapter 5: Poor reliability of measurement instruments to assess acute responses to load in soccer players irrespective of biological maturity status

Supplementary Table 10.8. Descriptive and standardized differences between trials for the Short Recovery and Stress Scale (SRSS) for the pre-PHV, at-PHV, and post-PHV maturity group.

Variable	Trial 1 (±SD)	Trial 2 (±SD)	Mean change (±SD)	ES (90%CL)	ES qualitative description
Pre-PHV maturity group, n=32					
Physical recovery	6.4±0.7	6.7±0.6	0.3±0.7	0.37 (0.00; 0.67)	small
Mental recovery	6.5±0.7	6.5±0.8	0.0±0.8	-0.04 (-0.38; 0.24)	trivial
Emotional recovery	6.3±0.8	6.5±0.8	0.2±0.9	0.24 (-0.11; 0.61)	small
Overall recovery	6.3±0.9	6.4±0.7	0.2±0.8	0.20 (-0.09; 0.54)	trivial
Physical stress	2.0±1.1	1.7±0.7	-0.3±0.8	-0.34 (-0.60; -0.11)	small
Mental stress	1.4±0.9	1.3±0.6	-0.1±0.8	-0.08 (-0.36; 0.28)	trivial
Emotional stress	1.5±0.7	1.4±0.9	-0.1±0.9	-0.11 (-0.45; 0.22)	trivial
Overall stress	1.6±1.0	1.3±0.7	-0.3±0.9	-0.29 (-0.58; -0.04)	small
At-PHV maturity group, n=34					
Physical recovery	6.2±0.9	6.1±0.9	-0.1±0.6	-0.10 (-0.31; 0.07)	trivial
Mental recovery	6.2±0.9	5.9±1.0	-0.2±0.7	-0.24 (-0.47; -0.06)	small
Emotional recovery	6.1±0.9	6.0±0.9	-0.1±0.6	-0.07 (-0.25; 0.15)	trivial
Overall recovery	5.5±1.2	5.6±1.3	0.1±1.1	0.10 (-0.16; 0.39)	trivial
Physical stress	2.4±1.4	2.2±1.4	-0.1±1.3	-0.08 (-0.36; 0.16)	trivial
Mental stress	1.9±1.2	1.9±1.2	0.0±0.8	-0.03 (-0.31; 0.13)	trivial
Emotional stress	1.8±1.1	1.6±0.8	-0.2±0.9	-0.18 (-0.43; 0.07)	trivial
Overall stress	2.1±1.2	2.1±1.2	0.0±1.1	0.00 (-0.30; 0.23)	trivial
Post-PHV maturity group, n=42					
Physical recovery	5.6±1.2	5.4±1.0	-0.2±1.3	-0.19 (-0.48; 0.11)	trivial
Mental recovery	5.8±1.1	5.8±0.9	0.0±1.2	0.05 (-0.25; 0.35)	trivial
Emotional recovery	5.7±1.3	5.8±1.2	0.1±1.4	0.06 (-0.23; 0.36)	trivial
Overall recovery	5.4±1.3	5.3±1.3	0.0±1.4	-0.04 (-0.33; 0.24)	trivial
Physical stress	2.8±1.5	2.7±1.2	0.0±1.5	-0.02 (-0.28; 0.29)	trivial
Mental stress	2.0±1.2	2.0±1.1	0.0±1.1	0.04 (-0.21; 0.27)	trivial
Emotional stress	2.1±1.4	2.2±1.4	0.1±1.2	0.09 (-0.13; 0.32)	trivial
Overall stress	2.2±1.1	2.5±1.3	0.3±1.4	0.21 (-0.08; 0.49)	small

Notes: ES=effect size, standardized difference

Supplementary Table 10.9. Descriptive and standardized differences between trials for the countermovement jump and leg stiffness for the pre-PHV, at-PHV, and post-PHV maturity group.

Variable	Trial 1 (±SD)	Trial 2 (±SD)	Mean change (±SD)	ES (90%CL)	ES qualitative description
Pre-PHV maturity group, n=31					
JH	24.3±3.8	23.8±4.4	-0.5±1.6	-0.11 (-0.26; 0.02)	trivial
RSImod	0.24±0.07	0.26±0.08	0.01±0.04	0.17 (-0.01; 0.34)	trivial
RFD	84.9±40.9	95.7±49.8	10.8±29.0	0.24 (0.07; 0.45)	small
EccI	0.86±0.22	0.92±0.23	0.06±0.15	0.26 (0.05; 0.44)	small
ConI	2.21±0.18	2.20±0.22	0.00±0.12	-0.02 (-0.21; 0.16)	trivial
EccV	0.59±0.16	0.64±0.17	0.05±0.12	0.33 (0.11; 0.52)	small
ConV	1.26±0.16	1.26±0.13	0.00±0.09	0.00 (-0.21; 0.18)	trivial
F@0V	8.7±3.1	9.3±3.2	0.6±2.2	0.19 (0.00; 0.42)	trivial
DurEcc	0.25±0.10	0.24±0.11	-0.02±0.10	-0.17 (-0.46; 0.20)	small
DurCon	0.32±0.07	0.31±0.05	-0.01±0.06	-0.16 (-0.50; 0.08)	trivial
CMD	0.30±0.05	0.30±0.06	0.00±0.04	0.06 (-0.16; 0.26)	trivial
Leg Stiffness	43.9±9.1	45.0±10.0	1.1±4.3	0.12 (-0.01; 0.25)	trivial
At-PHV maturity group, n=34					
JH	29.0±3.8	28.9±3.7	-0.1±1.6	-0.03 (-0.15; 0.10)	trivial
RSImod	0.34±0.08	0.36±0.06	0.01±0.04	0.18 (0.02; 0.38)	trivial
RFD	126.1±65.0	131.2±60.3	5.1±28.7	0.08 (-0.05; 0.23)	trivial
EccI	0.97±0.18	1.03±0.21	0.06±0.13	0.30 (0.13; 0.51)	small
ConI	2.44±0.17	2.44±0.16	-0.01±0.13	-0.03 (-0.32; 0.15)	trivial
EccV	0.67±0.15	0.70±0.15	0.03±0.12	0.18 (-0.06; 0.42)	trivial
ConV	1.42±0.13	1.42±0.12	0.00±0.06	0.01 (-0.14; 0.16)	trivial
F@0V	11.0±3.1	11.2±2.8	0.2±1.8	0.08 (-0.10; 0.26)	trivial
DurEcc	0.20±0.06	0.18±0.05	-0.01±0.04	-0.20 (-0.43; 0.00)	small
DurCon	0.27±0.05	0.26±0.05	-0.01±0.03	-0.11 (-0.33; 0.08)	trivial
CMD	0.28±0.06	0.28±0.07	0.00±0.04	0.00 (-0.19; 0.19)	trivial
Leg Stiffness	48.4±9.8	46.1±8.2	-2.4±6.6	-0.26 (-0.51; 0.01)	small
Post-PHV maturity group, n=42					
JH	34.0±3.6	33.5±3.8	-0.5±1.8	-0.14 (-0.28; -0.01)	trivial
RSImod	0.42±0.09	0.40±0.09	-0.01±0.05	-0.12 (-0.26; 0.02)	trivial
RFD	153.0±113.1	141.3±78.2	-11.7±73.8	-0.12 (-0.29; 0.11)	trivial
EccI	1.06±0.23	1.10±0.21	0.04±0.15	0.19 (0.01; 0.37)	trivial
ConI	2.66±0.17	2.62±0.16	-0.04±0.11	-0.27 (-0.43; -0.09)	small
EccV	0.75±0.18	0.75±0.15	0.00±0.09	-0.03 (-0.16; 0.12)	trivial
ConV	1.53±0.10	1.52±0.11	-0.02±0.08	-0.16 (-0.34; 0.03)	trivial
F@0V	13.2±4.0	12.4±2.9	-0.9±2.4	-0.25 (-0.42; -0.06)	small
DurEcc	0.18±0.05	0.18±0.05	0.00±0.03	0.03 (-0.21; 0.18)	trivial
DurCon	0.26±0.05	0.27±0.05	0.00±0.03	0.05 (-0.09; 0.18)	trivial
CMD	0.31±0.08	0.30±0.07	0.00±0.04	-0.02 (-0.18; 0.10)	trivial

Leg Stiffness	46.1±7.8	44.2±7.8	-1.9±4.3	-0.25 (-0.44; -0.09)	small

Notes: ES=effect size, standardized difference

Supplementary Table 10.10. Descriptive and standardized differences between trials for the submaximal run for the pre-PHV, at-PHV, and post-PHV maturity group.

Variable	Trial 1 (±SD)	Trial 2 (±SD)	Mean change (±SD)	ES (90%CL)	ES qualitative description
Pre-PHV maturity group, n=29					
HRex	178.5±8.9	179.8±8.8	1.2±3.9	0.14 (-0.00; 0.28)	trivial
HRR60s	59.7±9.3	59.8±12.7	0.2±11.4	0.01 (-0.32; 0.32)	trivial
At-PHV maturity group, n=28					
HRex	174.4±10.8	175.1±10.8	0.7±3.7	0.07 (-0.04; 0.18)	trivial
HRR60s	47.9±14.0	47.6±11.6	-0.3±10.3	-0.02 (-0.32; 0.19)	trivial
Post-PHV maturity group, n=36					
HRex	168.2±11.5	168.1±10.5	-0.2±4.0	-0.02 (-0.13; 0.08)	trivial
HRR60s	46.7±10.3	48.2±10.3	1.6±7.8	0.15 (-0.07; 0.37)	trivial

Notes: ES=effect size, standardized difference

10.2.3 Chapter 6: Are measurement instruments responsive to assess acute responses to load in high-level youth soccer players?

Supplementary Table 10.11. Description of all computed counter-movement jump (CMJ) variables

CMJ Variable	Unit	Abbreviation	Description
Jump Height	cm	JH	The maximum jump height achieved based on vertical take-off velocity: take-off velocity^2 ÷ 2g.
Reactive Strength Index modified	$m.s^{-1}$	RSImod	Ratio between jump height and total time to take-off.
Eccentric Rate of Force Development	$N.s^{-1}$	RFD	Largest force increase during a 30 ms epoch.
Eccentric Impulse	N.s	EccI	Force exerted during eccentric phase multiplied by the time of the eccentric phase.
Concentric Impulse	N.s	ConI	Force exerted during concentric phase multiplied by the time of the concentric phase.
Eccentric Velocity	$m.s^{-1}$	EccV	Mean velocity achieved during the eccentric CMJ phase.
Concentric Velocity	$m.s^{-1}$	ConV	Mean velocity achieved during the concentric CMJ phase.
Force at Zero Velocity	N	F@0V	Force when velocity is zero (transition from eccentric to concentric).
Duration of Eccentric Phase	ms	DurEcc	Time required to perform the eccentric CMJ phase.
Duration of Concentric Phase	ms	DurCon	Time required to perform the concentric CMJ phase.
Countermovement Depth	cm	CMD	The minimum (i.e. peak negative) displacement when velocity is zero (transition from eccentric to concentric).

Supplementary Table 10.12. Example process for statistical analysis

```
# packages

library(MASS) # build ordered logistic regression models
library(sjPlot) # create tables for models
library(nlme) # create linear-mixed models
library(rmcorr) # repeated-measures correlation
library(boot) # CI bootstrapping
library(knitr) # create generic tables

# Analysis of SRSS using ordered logistic regression models

## SRSS_Physical_Performance_Capability
### model
odds_KEB_kL <- polr(as.factor(SRSS_Physical_Performance_Capability) ~ as.factor(assessme
nt_time_cycle),
                  Hess = TRUE,
                  method = c("logistic"),
                  data = Data_raw_long_LMM)

### summary
summary(odds_KEB_kL)

tab_model(odds_KEB_kL,
         show.ci = 0.90)

## store table
odds_KEB_kL_table <- coef(summary(odds_KEB_kL))

## calculate and store p values
odds_KEB_kL_p <- pnorm(abs(odds_KEB_kL_table[, "t value"]), lower.tail = FALSE)*2

## combine tables
cbind(odds_KEB_kL_table, "p value" = odds_KEB_kL_p)

## calculate 90% CI
odds_KEB_kL_CI <- confint(odds_KEB_kL, level = 0.90)

## odds ratio
exp(coef(odds_KEB_kL))

## odds ratio with 90% CI
exp(cbind(OR = coef(odds_KEB_kL), odds_KEB_kL_CI))



# Analysis of parameters of the CMJ and submaximl run using linear mixed models

# Jump_Height
## model
lme_JH <- lme ( Jump_Height ~ assessment_time_cycle,
                  random = (~ assessment_time_cycle | player_ID),
                  weights = varIdent(form = ~ 1 | assessment_time_cycle),
                  corr = corAR1(form = ~ 1 | player_ID),
                  data = Data_raw_long_LMM)

## summary
summary(lme_JH)
```

```
## table
tab_model(lme_JH,
        show.ci = 0.90)

# phi
lme_JH$modelStruct$corStruct



# Standardised mean differences for parameters of the CMJ and submaximl run

# set seed
set.seed(1312)

## Jump_Height
### Subset variables, create dataframe, add a change score column
SMD_df_JH <- data.frame(Data_raw_long_0$`Jump Height`,
                        Data_raw_long_1$`Jump Height`) %>%
  drop_na() %>%
  dplyr::rename("pre" = "Data_raw_long_0..Jump.Height.",
                "post" = "Data_raw_long_1..Jump.Height.") %>%
  mutate(diff = post-pre)

### Function
SMD_function_JH <- function(data, indices) {
  d <- data[indices,]
  n_pre <- length(d$pre)
  n_post <- length(d$post)
  sd_pre <- sd(d$pre, na.rm = TRUE)
  sd_post <- sd(d$post, na.rm = TRUE)
  sd_pooled <- sqrt(((n_pre-1)*sd_pre^2 + (n_post-1)*sd_post^2) / (n_pre+n_post-2))
  m_diff <- mean(d$diff)
  ds <- m_diff/sd_pooled
  result <- c(ds)
}

### Boot function
SMD_boot_JH <- boot(SMD_df_JH, SMD_function_JH, R = 10000)


### Extract the values
SMD_CL_JH = boot.ci(SMD_boot_JH, conf = 0.90, type="bca")

### Create lists of ES and CL
SMD_names_JH = c("JH")
SMD_ES_JH = round(c(SMD_CL_JH$t0),2)
SMD_LL_JH = round(c(SMD_CL_JH$bca[4]),2)
SMD_UL_JH = round(c(SMD_CL_JH$bca[5]),2)

### create data frame with ES and CI
SMD_ES_CI_JH = data.frame(SMD_names_JH, SMD_ES_JH, SMD_LL_JH, SMD_UL_JH) %>%
  dplyr::rename("Parameter" = SMD_names_JH,
                "Effect Size" = SMD_ES_JH,
                "Lower Confidence Limit" = SMD_LL_JH,
                "Upper Confidence Limit" = SMD_UL_JH)

### final table with ES and CI for parameter
SMD_ES_CI_JH
```

```r
# Repeated-measures correlation for parameters of the SRSS, CMJ and submaximal run

# Jump Height
## total distance
rm_Total_JH_1_2 <- rmcorr(dataset = Data_delta_long,
      participant = `ID`,
      measure1 = `Total day-1&2 post measurement`,
      measure2 = `Jump Height`,
      CI.level = 0.90,
      CIs = c("analytic"),
      nreps = 10000,
      bstrap.out = TRUE)
rm_Total_JH_1_2

## high speed distance
rm_High_Speed_JH_1_2 <- rmcorr(dataset = Data_delta_long,
      participant = `ID`,
      measure1 = `High-Speed Distance day-1&2 post measurement`,
      measure2 = `Jump Height`,
      CI.level = 0.90,
      CIs = c("analytic"),
      nreps = 10000,
      bstrap.out = TRUE)
rm_High_Speed_JH_1_2

## sRPE
rm_sRPE_JH_1_2 <- rmcorr(dataset = Data_delta_long,
      participant = `ID`,
      measure1 = `sRPE day-1&2 post measurement`,
      measure2 = `Jump Height`,
      CI.level = 0.90,
      CIs = c("analytic"),
      nreps = 10000,
      bstrap.out = TRUE)
rm_sRPE_JH_1_2
```

10.2.4 Chapter 7: Psycho-physiological responses to a pre-season training camp in high-level youth soccer players

Supplementary Table 10.13. Description of all computed counter-movement jump (CMJ) variables

CMJ Variable	Unit	Abbreviation	Description
Jump Height	cm	JH	The maximum jump height achieved based on vertical take-off velocity: take-off velocity^2 ÷ 2g.
Reactive Strength Index modified	$m.s^{-1}$	RSImod	Ratio between jump height and total time to take-off.
Eccentric Rate of Force Development	$N.s^{-1}$	RFD	Largest force increase during a 30 ms epoch.
Eccentric Impulse	N.s	EccI	Force exerted during eccentric phase multiplied by the time of the eccentric phase.
Concentric Impulse	N.s	ConI	Force exerted during concentric phase multiplied by the time of the concentric phase.
Eccentric Velocity	$m.s^{-1}$	EccV	Mean velocity achieved during the eccentric CMJ phase.
Concentric Velocity	$m.s^{-1}$	ConV	Mean velocity achieved during the concentric CMJ phase.
Force at Zero Velocity	N	F@0V	Force when velocity is zero (transition from eccentric to concentric).
Duration of Eccentric Phase	ms	DurEcc	Time required to perform the eccentric CMJ phase.
Duration of Concentric Phase	ms	DurCon	Time required to perform the concentric CMJ phase.
Countermovement Depth	cm	CMD	The minimum (i.e. peak negative) displacement when velocity is zero (transition from eccentric to concentric).

Supplementary Table 10.14. Results the linear mixed models for the items of the Short Recovery and Stress Scale (SRSS). Data are presented relative to baseline (i.e., *D-3 Pre-Camp*).

Parameter	Fixed effects					Random effects		
	Estimate	Standard error	Degrees of freedom	t value	SD	SD Individual player ID	SD Skeletal age	SD Residual
Physical Performance Capability (AU)								
Intercept	4.80	0.21	13.8	22.53		0.61	0.32	0.35
D2 Camp	-0.32	0.36	10.8	-0.86	1.13			
D3 Camp	-0.31	0.19	11.7	-1.61	0.45			
D4 Camp	0.12	0.28	10.9	0.70	0.82			
D+1 Post-Camp	-1.18	0.21	10.4	-5.52	0.55			
D+4 Post-Camp	0.16	0.24	11.1	0.68	0.64			
Mental Performance Capability (AU)								
Intercept	4.90	0.25	11.2	19.37		0.65	0.53	0.31
D2 Camp	0.03	0.27	10.5	0.12	0.81			
D3 Camp	-0.14	0.27	10.6	-0.51	0.79			
D4 Camp	0.30	0.21	11.0	1.40	0.59			
D+1 Post-Camp	-0.43	0.26	10.5	-1.65	0.77			
D+4 Post-Camp	0.17	0.25	10.9	0.68	0.74			
Emotional Balance (AU)								
Intercept	5.18	0.26	11.4	20.0		0.64	0.52	0.39
D2 Camp	-0.17	0.17	17.9	-0.99	0.29			
D3 Camp	-0.65	0.26	10.8	-2.54	0.68			
D4 Camp	0.04	0.17	16.9	0.26	0.27			
D+1 Post-Camp	-0.71	0.34	10.4	-2.09	0.99			
D+4 Post-Camp	-0.01	0.15	33.0	-0.05	0.05			
Overall Recovery (AU)								
Intercept	4.76	0.24	11.9	20.23		0.68	0.29	0.45
D2 Camp	-0.53	0.30	10.5	-1.78	0.81			
D3 Camp	-0.69	0.31	10.0	-2.26	0.83			
D4 Camp	-0.12	0.33	10.3	-0.36	0.93			
D+1 Post-Camp	-1.41	0.26	9.4	-5.46	0.63			
D+4 Post-Camp	0.16	0.37	10.3	0.59	0.67			
Muscular Stress (AU)								
Intercept	1.08	0.32	11.3	3.37		0.86	0.61	0.44
D2 Camp	0.42	0.18	20.3	2.29	0.24			
D3 Camp	1.04	0.32	10.3	3.26	0.89			
D4 Camp	0.85	0.30	10.4	2.81	0.83			
D+1 Post-Camp	1.89	0.23	12.2	8.23	0.52			
D+4 Post-Camp	0.06	0.18	26.6	0.37	0.15			
Lack of Activation (AU)								
Intercept	0.97	0.44	10.5	2.21		0.50	1.34	0.35
D2 Camp	-0.33	0.38	10.8	-0.87	1.18			
D3 Camp	-0.12	0.51	10.8	-0.25	1.64			
D4 Camp	-0.52	0.44	10.7	-1.18	1.39			

D+1 Post-Camp	0.01	0.51	10.8	0.03	1.64			
D+4 Post-Camp	-0.33	0.38	10.7	-0.87	1.16			
Negative Emotional State (AU)								
Intercept	0.55	0.21	11.2	2.62		0.45	0.49	0.31
D2 Camp	0.26	0.17	11.1	1.51	0.40			
D3 Camp	0.03	0.17	10.7	0.19	0.39			
D4 Camp	0.00	0.18	10.2	-0.01	0.45			
D+1 Post-Camp	0.15	0.20	10.6	0.76	0.53			
D+4 Post-Camp	-0.01	0.17	10.8	-0.06	0.41			
Overall Stress (AU)								
Intercept	0.99	0.35	9.9	2.83		0.47	0.98	0.48
D2 Camp	0.06	0.27	7.9	0.22	0.63			
D3 Camp	0.34	0.41	10.8	0.82	1.21			
D4 Camp	-0.11	0.27	9.8	-0.42	0.64			
D+1 Post-Camp	1.41	0.26	9.0	5.45	0.60			
D+4 Post-Camp	-0.17	0.25	8.3	-0.68	0.56			

Supplementary Table 10.15. Results the linear mixed models for parameters of the countermovement jump (CMJ). Data are presented relative to baseline (i.e., *D-3 Pre-Camp*).

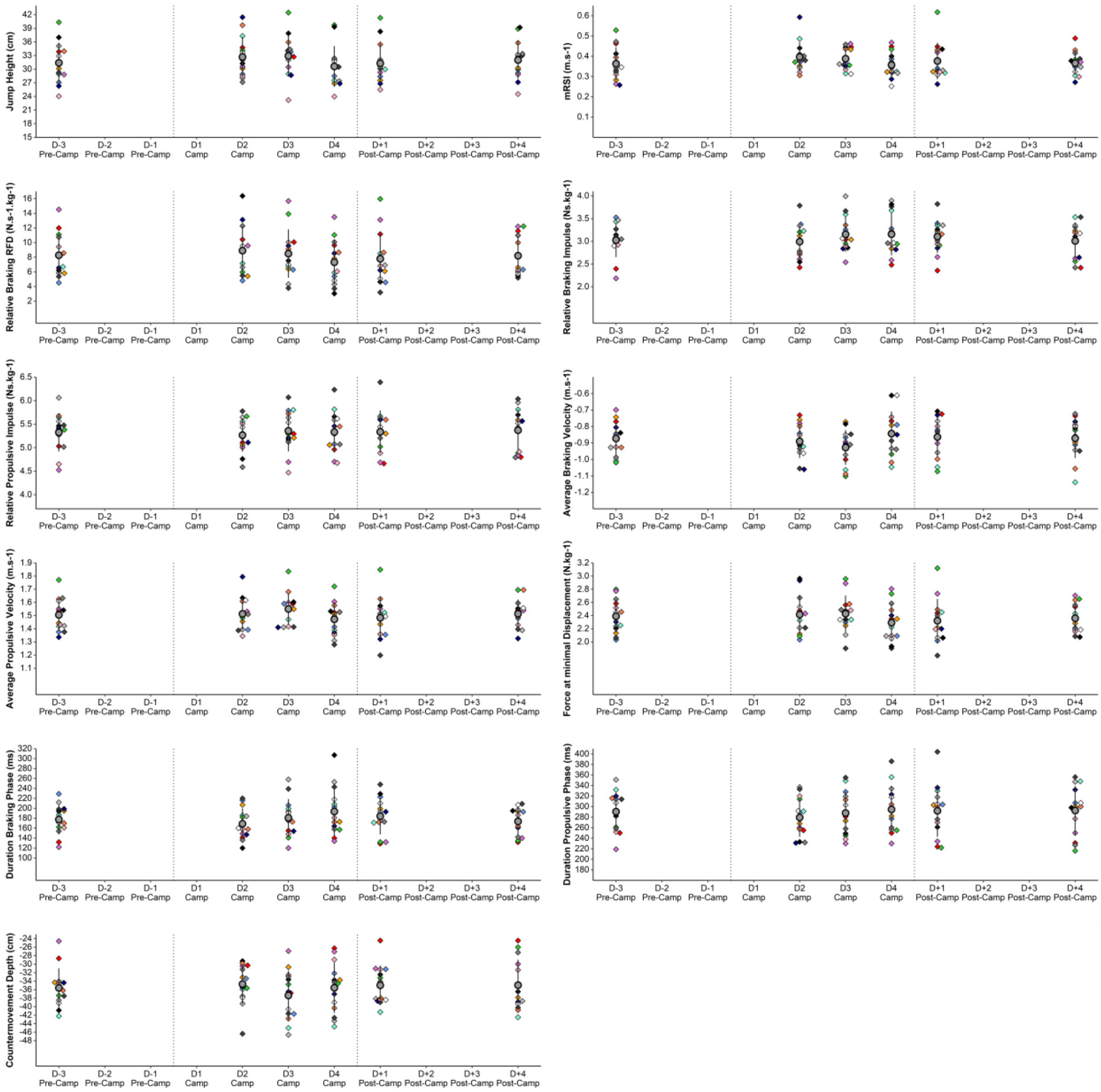
Parameter	Fixed effects					Random effects		
	Estimate	Standard error	Degrees of freedom	t value	SD	SD Individual player ID	SD Skeletal age	SD Residual
Jump Height (cm)								
Intercept	31.2	1.2	11.3	26.18		2.9	2.5	1.8
D2 Camp	1.3	1.6	10.5	0.86	4.6			
D3 Camp	1.7	0.7	23.6	2.31	0.8			
D4 Camp	-0.6	0.8	19.0	-0.75	1.2			
D+1 Post-Camp	-0.1	0.7	50.3	-0.09	0.2			
D+4 Post-Camp	0.7	0.7	38.9	0.97	0.5			
Reactive strength index modified (m.s-1)								
Intercept	0.36	0.02	10.9	16.38		0.03	0.05	0.05
D2 Camp	0.04	0.03	10.5	1.36	0.09			
D3 Camp	0.03	0.02	11.5	1.35	0.05			
D4 Camp	0.00	0.02	10.0	0.03	0.05			
D+1 Post-Camp	0.02	0.02	16.7	0.82	0.03			
D+4 Post-Camp	0.01	0.02	18.5	0.34	0.03			
Eccentric RFD (N.s-1.kg-1)								
Intercept	8.4	0.8	11.6	10.21		2.2	1.4	1.3
D2 Camp	0.9	1.2	10.6	0.81	3.6			
D3 Camp	0.3	0.5	42.2	0.56	0.2			
D4 Camp	-1.1	0.5	21.3	-2.07	0.6			
D+1 Post-Camp	-0.7	0.6	16.8	-1.21	1.0			
D+4 Post-Camp	-0.2	0.5	16.1	-0.41	0.8			

Eccentric Impulse (N.s.kg-1)								
Intercept	3.0	0.1	9.8	27.02		0.3	0.2	0.13
D2 Camp	-0.0	0.1	10.8	-0.19	0.2			
D3 Camp	0.1	0.1	10.1	1.35	0.2			
D4 Camp	0.1	0.1	9.1	1.52	0.2			
D+1 Post-Camp	0.1	0.1	12.3	1.49	0.1			
D+4 Post-Camp	-0.0	0.1	9.4	-0.12	0.2			
Concentric Impulse (N.s.kg-1)								
Intercept	5.3	0.1	11.7	42.00		0.2	0.3	0.2
D2 Camp	-0.0	0.1	10.7	-0.30	0.4			
D3 Camp	0.0	0.1	14.7	0.39	0.1			
D4 Camp	0.0	0.1	18.2	0.14	0.1			
D+1 Post-Camp	0.0	0.1	18.0	0.27	0.1			
D+4 Post-Camp	0.1	0.1	20.9	0.75	0.1			
Eccentric Velocity (m.s-1)								
Intercept	-0.86	0.03	12.1	-31.36		0.03	0.06	0.07
D2 Camp	-0.03	0.03	20.1	-1.07	0.04			
D3 Camp	-0.05	0.03	14.8	-1.80	0.05			
D4 Camp	0.05	0.03	11.0	1.41	0.07			
D+1 Post-Camp	0.02	0.03	13.2	0.67	0.07			
D+4 Post-Camp	0.01	0.04	10.9	0.29	0.08			
Concentric Velocity (m.s-1)								
Intercept	1.50	0.03	14.8	46.1		0.09	0.04	0.05
D2 Camp	0.02	0.05	10.6	0.46	0.14			
D3 Camp	0.05	0.02	28.5	2.40	0.02			
D4 Camp	-0.03	0.02	23.2	-1.33	0.03			
D+1 Post-Camp	-0.02	0.02	26.4	-1.15	0.02			
D+4 Post-Camp	0.01	0.02	49.5	0.43	0.00			
Force at Zero Velocity (N.kg-1)								
Intercept	2.4	0.1	16.9	35.78		0.2	0.1	0.1
D2 Camp	0.1	0.1	10.4	0.64	0.3			
D3 Camp	0.0	0.1	51.2	0.76	0.0			
D4 Camp	-0.1	0.1	19.4	-1.96	0.1			
D+1 Post-Camp	-0.1	0.1	16.8	-1.42	0.1			
D+4 Post-Camp	-0.0	0.1	19.8	-0.74	0.1			
Duration of Eccentric Phase (ms)								
Intercept	178	9	10.2	20.11		26	13	14
D2 Camp	-10	9	10.2	-1.11	24			
D3 Camp	0	7	13.4	0.04	13			
D4 Camp	16	11	10.0	1.37	33			
D+1 Post-Camp	8	6	14.9	1.29	11			
D+4 Post-Camp	-3	6	9.4	-0.49	11			
Duration of Concentric Phase (ms)								
Intercept	288	12	13.3	23.56		32	23	19
D2 Camp	-9	13	11.0	-0.69	36			
D3 Camp	-3	8	21.3	-0.32	11			

D4 Camp	5	8	36.9	0.60	5			
D+1 Post-Camp	2	8	29.7	0.29	7			
D+4 Post-Camp	3	7	41.6	0.37	4			
Countermovement Depth (cm)								
Intercept	-35.0	1.3	10.1	-26.25		2.8	3.11	2.06
D2 Camp	0.6	1.3	10.2	0.49	3.4			
D3 Camp	-1.2	1.3	10.4	-0.97	3.3			
D4 Camp	0.6	1.1	12.4	0.55	2.5			
D+1 Post-Camp	0.7	1.2	9.6	0.55	3.1			
D+4 Post-Camp	0.7	1.2	10.5	0.62	2.8			

Supplementary Table 10.16. Results the linear mixed models for parameters of the sub-maximal run. Data are presented relative to baseline (i.e., *D-3 Pre-Camp*).

Parameter	**Fixed effects**					**Random effects**		
	Estimate	**Standard error**	**Degrees of freedom**	**t value**	**SD**	**SD Individual player ID**	**SD Skeletal age**	**SD Residual**
HRex (bpm)								
Intercept	185.4	2.3	8.8	81.75		5.4	5.1	2.7
D2 Camp	-1.4	1.1	15.4	-1.24	1.4			
D3 Camp	-6.8	1.2	8.7	-5.43	2.2			
D4 Camp	-	-	-	-	-			
D+1 Post-Camp	-	-	-	-	-			
D+4 Post-Camp	-4.1	1.2	5.9	-3.38	1.9			
HRR60s (bpm)								
Intercept	47.1	3.1	10.5	15.41		6.2	7.9	3.2
D2 Camp	2.0	1.8	10.3	1.09	4.4			
D3 Camp	1.0	2.7	10.6	0.38	7.9			
D4 Camp	-	-	-	-	-			
D+1 Post-Camp	-	-	-	-	-			
D+4 Post-Camp	10.4	2.9	10.5	3.55	8.8			



Supplementary Figure 10.1. Mean ±SD as well as individual values for all CMJ parameters across the three time periods (pre-camp, camp, and post-camp).