



UNIVERSIDADE D  
COIMBRA



João Pedro Marques Duarte

**ISOKINETIC KNEE JOINT MUSCLES STRENGTH:**  
reproducibility of conventional and functional ratios and  
multilevel developmental changes in young soccer players

**Thesis for the degree of Doctor of Sport Sciences in the branch of Sports Training supervised by  
Prof. Dr. Manuel J. Coelho-e-Silva, Prof. Dr. André Seabra and Prof. Dr. Robert M. Malina,  
submitted to the Faculty of Sport Sciences and Physical Education of the University of Coimbra.**

August of 2018

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*“We did not ask for this room or this music.*

*We were invited in.*

*Therefore, because the dark surrounds us, let us turn our faces to the light.*

*Let us endure hardship to be grateful for plenty.*

*We have been given pain to be astounded by joy.*

*We have been given life to deny death.*

*We did not ask for this room or this music.*

*But because we are here, let us dance.”*

*Stephen King, 1963*

To me, to my family, friends, and Professors.







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# Abstract

The present Thesis has been divided into four sections and the main purpose was to gain more understanding of the relationship between (the development of) lower-limb muscular strength and body size and composition and biological maturation, using a multidisciplinary approach. The first part provides an exhaustive description of the participants considered in different studies, well as the material, methods, and variables assessed. The second section includes strength assessment considering a wider spectrum of knee joint angular positions. Test-to-test variation in isokinetic assessments was based on repeated tests within a period of 1-week. Overall, these cross-sectional studies highlighted that: (i) assessment of the KF to extensors strength ratio at the same knee-joint angle provide a more functionally relevant measurement; (ii) the ability of the muscles to control the joint is influenced by the angular position; (iii) functional ratios derived from angular positions near to full knee extension show higher disparities than flexed angles; (iv) ecc Hamstring muscle action is less effective in extended knee positions. These angular positions represent a range where the injury is most likely to occur.

Given the relatively limited data for youth athletes, in third section, longitudinal data are presented on adolescent male soccer players that have been followed across time. In the preceding context, these studies aimed to investigate the independent and interactive contributions of body size and composition, biological maturation to inter- and intra-individual development of knee joint strength and emphasized that: (i) CA was a significant explanatory variable once body size, body composition, and maturation were taken into account; (ii) stature might not play a major role in the development of isometric strength actions; (iii) in cc muscle action, the increase in stature introduces an assessment mechanical advantage that occurs in conjunction with growth; (iv) ELL significantly contributes to isokinetic KFecc:KFcc; (v) using whole body mass as a covariate may be inappropriate when examining localized muscle groups; (vi) there are moderate to strong correlations between knee extension and flexion peak torque and FFM; (vii) the introduction of

DXA preferred thigh LST was found to be a significant explanatory variable in the development of functional extension (KFecc:KEcc).

The last section comprises the general discussion in which the findings of the various studies are summarized and put into context and their implications discussed. Our work allowed quantifying the impact of the principal modifiable determinants of strength parameters. Multilevel modelling has the potential to provide useful information in the explanation of inter-individual differences at a certain age and probably more important to predict and explain changes over time, allowing a critical interpretation of variation within and between individuals.

**Keywords:** muscle strength; knee joint stability; peak torque; angle-specific; growth; skeletal maturation; developmental changes.

## *Resumo*

A presente Tese está dividida em quatro secções e tem como objetivo principal a compreensão da relação entre (o desenvolvimento da) a força muscular do membro inferior, o tamanho e composição corporal, e a maturação biológica, usando uma abordagem multidisciplinar. A primeira parte proporciona uma descrição exaustiva dos participantes considerados nos diferentes estudos, bem como do material, dos métodos e das variáveis avaliadas. A segunda secção inclui a avaliação da força considerando um espectro alargado de posições angulares na articulação do joelho. A variação teste re-teste nas avaliações isocinéticas foi baseada em períodos de uma semana. De um modo geral, os estudos transversais salientam que: (i) a avaliação da relação de força dos músculos flexores e extensores do joelho, na mesma posição angular, proporciona uma medição mais funcional; (ii) a capacidade muscular para controlar a articulação do joelho é influenciada pela posição angular; (iii) os rácios funcionais obtidos em posições angulares próximas à extensão completa da articulação do joelho mostram maiores disparidades em relação a ângulos próximos da flexão; (iv) a ação muscular excêntrica é menos eficaz em posições próximas da extensão completa do joelho. Estas posições angulares representam uma amplitude onde mais provável ocorrer lesão.

Uma vez que existem dados limitados considerando populações de atletas, a terceira secção examina, através de dados longitudinais, jogadores de futebol masculinos adolescentes seguidos durante o tempo. Assim, estes estudos visam investigar as contribuições independentes e interativas do tamanho e composição corporal e da maturação biológica no desenvolvimento inter e intra-individual da força muscular na articulação do joelho, e enfatizam que: (i) a idade cronológica é uma variável explicativa significativa, mesmo quando o tamanho e composição do corpo e a maturação foram tidos em conta; (ii) a estatura não desempenha um papel importante no desenvolvimento da força muscular isométrica; (iii) na ação muscular concêntrica, o aumento da estatura introduz uma vantagem mecânica de avaliação que ocorre em conjunto com o crescimento; (iv) o comprimento estimado dos



membros inferiores contribui significativamente para o rácio funcional de extensão; (v) a utilização da massa corporal total como covariável pode ser inadequada ao examinar grupos musculares localizados; (vi) existem correlações consideradas entre moderadas e fortes entre o pico de torque dos movimentos de flexão e extensão do joelho e a massa isenta de gordura; (vii) a introdução da variável tecido magro mole avaliado pela metodologia DXA na coxa do membro inferior preferido revelou-se significativa e explicativa no desenvolvimento do rácio funcional do movimento de extensão.

A última secção compreende a discussão geral, na qual os resultados dos vários estudos são resumidos e as suas implicações práticas contextualizadas. O nosso trabalho permitiu quantificar o impacto das principais determinantes modificáveis nos parâmetros de força do membro inferior. A modelação multinível tem o potencial de fornecer informações úteis na explicação das diferenças entre indivíduos de uma determinada idade e de prever e explicar as mudanças ao longo do tempo, permitindo uma interpretação crítica da variação intra e inter-individual.

**Palavras-chave:** estabilidade articular do joelho; pico de torque; ângulo-específico; crescimento; maturação esquelética; mudanças de desenvolvimento.

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# List of Abbreviations

CA	chronological age
cc	concentric muscular action
CI	confidence intervals
CNS	central nervous system
CV	coefficient of variation
DXA	Dual-energy X-ray Absorptiometry
ecc	eccentric muscular action
ELL	Estimated leg length
f	absolute frequencies.
FFM	fat-free mass
FM	fat mass
ICC	intra-class correlation
im	isometric muscular action
KE	knee extensors
KF	knee flexors
LLA	lower limits of agreement
LST	lean soft tissue
M1	time-moment 1
M2	time-moment 2
NS	not significant
PT	peak torque
REM	random effects models
ROM	range of motion
RUS	radius, ulna, short bones
SA	skeletal age
SD	standard deviation
SEE	standard error of estimate (SEE)
SEM,	standard error of the mean
T	torque

TEM	technical error of measurement
TW	Tanner-Whitehouse
ULA	upper limits of agreement

**Section**

**I**

**Introduction and Methods**

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# **Chapter I**

---

**General introduction**



# 1. General introduction

Sports participation is the main form of physical activity during the second decade of life that encompasses variation in timing and tempo of changes in body size, proportionality, body composition and biological maturation (Malina, Bouchard, & Bar-Or (2004). In the specific case of Portugal and according to the Portuguese Institute of Sports (2016), the sport is the major form of physical activity among children and youth. Participants have increased from 260000 (1996) to >590000 (2016). Soccer is the most popular sport, with 168000 participants (FIFA, 2007), and academies are searching for talents. The best soccer players are attracted to long-term programs at very early ages. The social harassment phenomenon to be engaged in programs with limited physical, motor, emotional and social experiences is probably related to the dramatic increment of sports injuries. Prevalence of injuries is now reported for soccer players aged 12-19 years (Brito et al., 2012).

The major longitudinal studies that provide information on growth and maturation began in the United States in the 1920s and 1930s (University of California; FELS Research Institute in South Ohio (Ulijaszek, Johnston, & Preece, 1998)). Later, school-based studies conducted in Europe (The Leuven Growth Study and The Amsterdam Growth Study) provided longitudinal information on physical fitness with supplemental interests on health-related outputs, physical activity, and lifestyle (Simons et al., 1990; Kemper, 1995). These studies were mainly designed to produce normative standards. Developmental changes in metabolic and physiological parameters are less extensive in the literature.

The TOYA (Training of Young Athlete) study used a linked longitudinal design, following five age groups cohort from four sports (tennis, soccer, swimming and gymnastics). It was possible to obtain multilevel models on lung function and aerobic fitness. This analytical technique may be interpreted as a longitudinal extension of multiple regression analysis. Studies using multilevel modelling seemed more abundant in non-athletic young people: peak power outputs derived from



Wingate test (Armstrong, Welsman, Williams, & Kirby, 2000) and from Force-Velocity test (Santos, Armstrong, De Ste Croix, Sharpe, & Welsman, 2003); peak oxygen uptake during growth and maturation (Armstrong & Welsman, 2001) and isokinetic strength (De Ste Croix, Armstrong, Welsman, & Sharpe, 2002; De Ste Croix, Deighan, Ratel, & Armstrong, 2009).

Due to the lower existence of studies in the literature concerning neuromuscular mechanisms, there is a need to study, according to a developmental perspective, the use of longitudinal data and tempo variations of a stroke associated to the production of neuromuscular strength evaluated by the isokinetic dynamometer. This study was designed to extend a cross-sectional research. Longitudinal interpretation is crucial for multilevel modeling of isokinetic strength outputs including conventional and functional ratios of knee flexors (KF) and extensors (KE) taking into account contrasting angular velocities throughout the range of motion.

## 1.1. Study object

Practiced by children and adults, men and women, soccer is the most performed sport in the world (Reilly, Williams, Nevill, & Franks, 2000). It is estimated that there are 265 million people who play the sport along with more than 5 million referees (FIFA, 2007). In the specific case of Portugal, soccer occupies a position of great prominence, with an increase of 43% (95746 to 168097) in the number of participants in the two last decades (Portuguese Institute of Statistic, 2016). Participation in youth team sports is based primarily on chronological age groups, which often span 2 years. In Portugal, competitive soccer models start at age 9 and represent about 32% of youth participating in organized and competitive sports (Portuguese Institute of Statistic, 2016). Variation in size, function, and skill associated with age *per se* and with maturity status within 2-year age groups can be considerable. As stated by the Portuguese Soccer Federation (2017/2018), all soccer players can be registered “[...] according to respective age in the respective stage:

under-7; under-9; under-11; under-13 (classified as infantiles); under-15 (classified as initiates); under-17 (classified as juveniles) and under-19 (classified as juniors)".

In the past years, soccer received a growing importance recognized, not only by the media but also by its capacity and pedagogical interest, which ultimately give it priority status in various programs and institutions. According to Malina et al. (2005), youth sports participation increases proportionally with chronological age but undergoes a subsequent decline during the transition to adolescence, around 12-13 years of age, and during the period of adolescence itself. Soccer is organized in a selective perspective but at the same time has the ability to attract the massive public, which uses soccer practice through the power of your attractiveness and well-being. In this sense, it can be stated that soccer is an instrument of public health (Seabra et al., 2012).

Soccer critical moments frequently consist of high-intensity short-term efforts, either with or without the ball (Sliwowski, Jadczyk, Hejna, & Wiczorek, 2015). Soccer activity requires intermittent explosive-type efforts, such as jumps, duels, kicks, tackles, sprints, brakes and changes of direction, which depend on the efficiency of the neuromuscular system, particularly of the lower limbs (Cometti, Maffiuletti, Pousson, Chatard, & Maffulli, 2001). It is well known that soccer players usually have a preferred leg for kicking, passing and controlling the ball (Capranica et al., 1992), and this preference is the possible cause of asymmetry between the two legs, or between the agonist and antagonist muscles (Sliwowski et al., 2015). These differences in strength profiles are considered to be an important predictor of injury in soccer players (Fousekis, Tsepis, Poulmedis, Athanasopoulos, & Vagenas, 2011).

## **1.2. The adolescent years**

According to Malina et al. (2004), children and adolescents are involved in three processes that interact with each other: growth, maturation, and development. Although, these terms seem similar they are, in fact, different factors that are present in the lives of children and young people, roughly in the first two decades of life.

The age at which these changes take place may be termed as “puberty” or “adolescence”.

Growth is meant to increase the body, in size, as a whole, and by parts. According to Stratton et al. (2004) growth refers, in biological terms, to a combination of the increase in the number of cells (hyperplasia: occurs primarily before birth) and the increase in size (hypertrophy: occurs after birth). Although they present similar growth patterns, the different parts of the body grow at different rates, resulting in changes in the momentary bodily proportions. As the child grows, tends to become taller and heavier, also increase the lean and fat tissues, as well as the organs increase in size. During the interval of maximum growth in stature (i.e., 13-15 years in boys) boys gain about 14kg in fat-free mass (FFM) and 1.5kg of fat mass (FM) (Malina et al., 2004). The differences that are in terms of body proportions, caused by the different rhythms of the body's growth, are visible for example in the lower limb. The legs grow faster than the torso during childhood, and the child is momentary, with a relative lower limbs size to stature disproportion (Malina et al., 2004). Therefore, variation within and between individuals in body size, composition, proportions and biological maturation can be considerable.

Maturation refers to the process of developing the different functions of the organism with a view to biological maturity. The "timing" and "tempo" (rate) of maturation are considerably variable between different individuals (Malina, 2004). The "timing" refers to the moment when the maturation event takes place (i.e. age of menarche in girls, the age of onset of the first pubic hairs in the boys). "Tempo" refers to the pace of maturation progress (i.e. the speed at which the young man passes through the puberty growth jump. Resuming, maturation refers to progress towards the mature state, being an operational concept, since each state of maturation varies depending on the body system analyzed.

Last, the concept of development, according to Malina et al. (2004) relates to the acquisition of qualitative skills (Stratton et al., 2004) and behavioral, that is, the learning of appropriate behaviors that are expected by society. As the child engages

in life at home, in school, in sport, etc., it develops in cognitive, social, emotional and moral terms, learning to behave in a culturally appropriate manner (Malina, 2004). The three processes, growth, maturation and development, occur at the same time and interact with each other. They interact to influence the child's self-concept, self-esteem, body image, and perceived competence (Malina et al., 2010).

### **1.3. Biological maturation**

Status and timing are two perspectives of biological maturation. The former refers to the state of maturation at the time (chronological age, CA) of observation, while the latter refers to the CA at which specific maturational landmarks are attained. Skeletal maturation is assumed to be the best method for evaluating biological maturation (Malina & Bouchard, 1991; Beunen et al., 1997; Malina et al., 2004; Stratton et al., 2004; Figueiredo, Goncalves, Coelho-e-Silva, & Malina, 2009; Malina, Rogol, Cumming, Coelho-e-Silva, & Figueiredo, 2015). The skeleton develops from the cartilages in the prenatal period until it consists of fully developed bones in adulthood. The evaluation of the skeletal age (SA) is based on the idea that a more developed child will have a larger amount of bone constituted and of lesser cartilage compared to a less advanced child in maturational terms (Faulkner, 1996).

The skeleton maturation can be examined through the use of X-rays. Different bone structures can be used for this purpose, emphasizing the joints of the knee, tarsus, and foot, and the hand and handle, the latter being the most used and referenced by the scientific community (Beunen et al., 1997; Malina et al., 2004). Although there is a differentiated cadence in the maturation of different bone structures, it is believed that the structure given by the bones of the hand and the fist is reasonably the skeleton as a whole (Malina et al., 2004). Traditionally, a hand-x-radiography of the left hand and wrist is used, in particular: radius, ulna, carpals, metacarpals and, phalanges of the first, third and fifth finger.

SA–CA is an indicator of biological maturity status at the time of observation and is used most often to evaluate the level of maturity of the bones of the hand-wrist relative to the reference sample. The Fels method is based on American youth samples (Fels longitudinal study) and although the Tanner-Whitehouse method (TW) was initially based on 3000 British children, the most recent version is based on a combined sample of Italian, British, Belgian, Spanish, Argentine, American and Japanese youth. The two methods are similar in the principle, but criteria and procedures vary so that SAs assigned with each method are not equivalent.

Participants in the Longitudinal Study Fels (Roche, Chumlea, & Thissen, 1988) were considered for the Fels method. This sample comprised children from middle socio-economic strata of south-central Ohio, participants in the Longitudinal Study Fels (Roche, Chumlea, & Thissen, 1988). This methodology is based on the observation of 22 bones (radius, ulna, large bones, unciforme, pyramidal, pisiform, ulnar, scaphoid, trapezium, trapezoid, 1<sup>st</sup>, 3<sup>rd</sup> and 5<sup>th</sup> metacarpals, 1<sup>st</sup>, 3<sup>rd</sup> and 5<sup>th</sup> proximal phalanges, adductor sesamoid, 3<sup>rd</sup> and 5<sup>th</sup> intermediate phalanges, 1<sup>st</sup>, 3<sup>rd</sup> and 5<sup>th</sup> distal phalanges) in a total of 98 different assessment criteria. The evaluation criteria consider whether or not the ossification center exists, the ossification points, the shape of the bones, the opaque lines inscribed on each bone and the ratio between the pineal and the metaphysis of the long bones. The age and gender of the individual determine the bones and criteria, in each bone, that will serve for the estimation of the SA, which always has an associated standard error. This procedure is not verified in the other methods.

The subjects classification is performed by subtracting the CA from the bone age creating the following subgroups (Malina et al., 2010): **late** (delayed/late mature), when the bone age was lower than the chronological age in more than 1 year; **on time** (average/on time mature), when the bone age was within the range of more or less a year in relation to the chronological age; **advanced** (Advanced/early mature), when the bone age was higher than the CA in more than 1 year. If an individual has attained skeletal maturity, a SA is not assigned; the individual is

simply noted as skeletally mature. With the Fels method, a SA of 18.0 years indicates maturity.

The TW metho (Tanner, Whitehouse, & Healy, 1962; Tanner, Whitehouse, Marshall, Healy, & Goldstein, 1975; Tanner, Healy, Goldstein, & Cameron, 2001) of determining the SA was known as the bone-specific approach since it centralizes in the observation and evaluation of each bone in the development state of the different indicators. Originally this method was developed from a sample of approximately 3000 healthy British children (Tanner et al., 1962), seeking to confront certain characteristics of 20 left hand and wrist bones, given by an X-ray, with a set of criteria at the stages of development why all the bones have to go through to their mature state.

The successive versions used the achievement of maturation scores (from zero to 1000) that are subsequently transformed, based on reference tables, in SA. With the emergence of the first revision of this method: TW2 (Tanner et al., 1975). The scoring system has been altered but the maturational indicators have not undergone alteration. The TW2 method distinguished the carpal bone age, based on the evaluation of the seven carpal bones and the RUS bone age (radius, ulna and short bones) based on the evaluation of the 13 original long bones beyond the bone age given by the set of the 20 bones. Separate scoring systems were also created for carpal and RUS bone ages. This distinction is justified by the fact that the carpal bones tend to mature earlier than the long ones. However, the use of the RUS age alone leads to an evaluation based only on 13 bones.

The TW3 method (Tanner et al., 2001) was the last revision of this methodology. In this version two changes were made: only the carpal and RUS bone ages (the bone age given by the whole of the 20 bones were no longer considered); and there was an increase and diversification of the reference sample, including data on populations from various countries from different continents, as cited before. As a result, the tables for the conversion of age have undergone changes. However, the

criteria for the maturational evaluation of each of the bones and the scores assigned to each of these criteria remained unchanged.

## **1.4. Strength development**

Muscular strength has been defined as the ability to exert a force on an external object or resistance (Suchomel, Nimphius, & Stone, 2016). Some of the most common movements in soccer are jumping, sprinting, and rapid change of direction tasks (Wisloff, Castagna, Helgerud, Jones, & Hoff, 2004). Muscular strength can have a significant influence on important force-time characteristics related to soccer performance.

### *Contractable element*

Skeletal muscle is constituted in its central zone by a muscular womb and tendons for muscle insertion (usually in the bone) (Enoka, 2008). The muscular womb is the place where muscle strength is produced. It is constituted, mainly by the muscular fibers that through contractions produce strength and mechanical work. In the muscular womb, the membranes create a conjunctival network: epimysium, perimysium, and endomysium.

### *Muscle mass increase*

Weight training increases strength production capacity and consequently the muscular transverse area ( $\text{cm}^2$ ) and its volume ( $\text{cm}^3$ ). An interventional study with the duration of 6 months considering weight training on alternate days with six series of eight unilateral leg extensions at 80% of one repetition maximum, concluded that effect of this type of training increase torque performance per unit area and may indicate changes in muscle architecture (Narici et al., 1996).

## Muscle actions

When activated the muscle develops tension and tend to shorten, may or not occur displacement of the bony segments associated with them. The type of external resistance will determine whether or not the movement exists. Classically there are three types of muscular actions: isometric, concentric, and eccentric muscular actions (Enoka, 2008).

**Isometric muscular action (im)** can be defined as if the tension developed by the muscle is equal to the resistance that it has to overcome; the length of the muscle fibers remains essentially unchanged. This type of muscle action occurs when the intention to exert strength against immovable resistance. Isometric strength tests have been used to examine different phases of an exercise (Beckham et al., 2012), the effect of a training program (Bazyler, Beckham, & Sato, 2015), and to determine force production differences among different sports (McMaster, Gill, Cronin, & McGuigan, 2014; Bailey, Sato, Burnett, & Stone, 2015).

Dynamic strength testing may be the most common method of measuring an individual's strength (Suchomel, et al., 2016). The **concentric muscular action (cc)** is revealed when the tension developed by the muscle is superior to the resistance that it has to overcome, a shortening occurs. This type of action takes place in the positive phase of most strength training exercises, such as bench press or squat. Previous research has investigated the use of dynamic strength tests to examine the effect of specific training programs (Rønnestad, Nymark, & Raastad, 2011), the effect that a competitive season had on concentric muscular strength (Garcia-Garcia, Serrano-Gomez, Hernandez-Mendo, & Tapia-Flores, 2016), and the contributing factors that affect change of direction performance (Spiteri, et al., 2014).

Reactive strength can be well defined as the capacity of an individual to change rapidly from an eccentric to concentric muscular action (Young, 1995). **Eccentric muscular action (ecc)** is triggered when the tension developed by the muscle is lower than the resistance it has to overcome, although the muscle tries to



shorten, there is an elongation of the muscle fibers. This type of action takes place in the negative phase of most strength training exercises, such as bench press or squat. Reactive strength testing can provide additional information regarding how an individual achieves a certain standard of dynamic/functional performance (Suchomel, et al., 2016). Previous research has determined that reactive strength assessment is reliable (Lloyd, Oliver, Hughes, & Williams, 2009), can distinguish between field athletes with higher or lower acceleration abilities (Lockie, Murphy, Knight, & Janse de Jonge. 2011), can be used to monitor neuromuscular fatigue and as an indicator of the current training conditions (Suchomel, et al., 2016).

It should also be considered the natural and functional form of muscular activity. In movements of locomotion, such as gait, race, and jump, the extensor muscles of the lower limbs are permanently subjected to impacts on the soil that cause a muscular elongation followed by a shortening phase. Usually, in the specific sporting gestures, the muscles do not act in a purely isometric, concentric or eccentric way. Komi (1984) describes this phenomenon as a muscle cycle stretching-shortening. The muscular operation is independent of the other forms of force manifestation and is regulated, by the quality of the nervous activation pattern of the muscles involved (i.e., the balance between the facilitating nerve factors and inhibitors of muscular contraction).

#### Intermuscular coordination (antagonist-agonist strength relationship)

In addition to the management of muscular contraction, the Central Nervous System (CNS) has to ensure coordination between all muscles involved in function and muscular action (Enoka, 2008). In a given process of strength training, regardless of the used method, the first adaptations are of an intermuscular nature. At the end of the first few weeks, the antagonist-agonistic relationship improves substantially and can be a technical learning process (Enoka, 2008).

The muscles that go through the mobilized joint and that have their line of traction oriented according to the direction of movement are considered as muscles agonists (Enoka, 2008). Within this group of muscles, it is possible to distinguish those who always participate in the execution of the movement (i.e., main agonists), of those who only intervene in a meaningful way in more demanding conditions of speed or load (i.e., agonists) (Enoka, 2008).

At the knee joint flexion movement, the thigh posterior muscles are considered mainly agonists, while the gastrocnemius are secondary agonists. The CNS is responsible for this management (medullar) of relations' activity between synergistic muscle groups, taking into account the size (muscular length), the distance between the insertion and the mobilized joint or the percentage of the different muscle fibers type (Enoka, 2008).

The antagonist-agonist ratio implies that at the level of the CNS there is a joint control of the motoneurons of the activated muscles (Enoka, 2008). There are two types of antagonist-agonist coordination pattern: co-contraction (standard that ensures an increase in joint stability; the antagonist contraction locks the movement from its beginning, thus being ineffective in the production of rapid movements) and reciprocal innervation (short and well-defined impulses; antagonistic contraction only starts at the end of the agonist pulse) (Brown & Gilleard, 1991). The most important manifestation of a pattern of reciprocal innervation is present in fast actions that have to be slowed down (i.e. kicking in soccer).

### Knee joint imbalances

Initially, the antagonist-agonist imbalance was defined as a deviation of 10 percent or more from the mean value for a specific joint (Grace, Sweetser, Nelson, Ydens, & Skipper, 1984). Literature also confirmed an increased risk of ligamentous damage in athletes with KF-to-KE strength imbalances and reduced Hamstrings-Quadriceps coactivation patterns (Baratta et al., 1988). According to the same group of authors,

the ligaments associated with joints are responsible for its stability, and coactivation of the antagonist is essential to aid in maintaining joint control.

Primarily, the KF:KE has been calculated as knee flexion moment divided by knee extension moment attained at the same angular velocity and contraction mode (im, cc, ecc). This labeled conventional KF:KE simply indicates the degree of qualitative similarity between the KF and KE moment-velocity patterns (Aagaard, Simonsen, Trolle, Bangsbo, & Klausen, 1995). A functional KF:KE is more appropriated once the conventional approach has the limitation that cc muscle contraction did not occur simultaneously in antagonistic muscle groups (Coombs & Garbutt, 2002). The KFecc:KEecc indicates the magnitude to which the KF muscles are capable of activating to counteract the anterior tibial shear force produced by maximal KEecc contraction. Functional knee joint movement encompasses KFecc muscle contraction to be paired with KEecc muscle contraction during knee extension, and vice-versa: KFcc muscle contraction paired with KEecc muscle contraction during knee flexion. Values of 1.00 for isokinetic open chain knee extension have been previously reported (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998), and indicate a significant capacity of the KF to provide dynamic joint stabilization during active KE. Contrary, lower values of 0.30 have been reported for functional KFcc:KEecc ratios representative of isokinetic open chain knee flexion (Aagaard et al., 1998).

### Isokinetic dynamometer assessment

Isokinetic dynamometry assessment has become a favored method for the assessment of static and dynamic muscle function in both rehabilitation and sports environments (Gleeson & Mercer, 1996). Isokinetic equipment, in addition to providing an accommodating resistance, implies that the angular velocity is constant. The resistance is controlled electronically by a coupled computer and in each angular position; the equipment offers a resistance proportional to the force developed by the individual. This type of equipment is usually used for the assessment and monitoring

of training and rehabilitation. This method permits the assessment of the muscular forces in static and dynamic conditions and provides optimal muscle loading (Baltzopoulos & Brodie, 1989).

On the other hand, isokinetic equipment is safety equipment as it allows to work with very low loads and to graduate its progressive increase with a complete control of various parameters. This type of equipment is usually uniting, which means that one can easily isolate a certain muscle group, but it is not so easy, or even impossible, to perform a closed kinetic chain exercise.

The most commonly used isokinetic parameters include the peak torque (PT) and the angular position where it was recorded; the torque (T) output at different angular velocities, the T ratio of reciprocal muscle groups and the T output during repeated contractions.

### **1.5. Maturity-associated variation in growth and strength performance**

Individual maturity status and body dimensions differences influence performance (Beunen & Malina, 1988). According to the same authors, compared with the general population, successful youth athletes tend to differ, on average, on maturity status and growth rate. Maturity status variation influences body dimension, composition and proportions and also motor performance (Malina et al., 2004).

In which concerns male athletes in team sports, including soccer, the literature suggests that the elite adolescent tend to be advanced in skeletal maturation especially after 14 years age (Malina, 1968). Furthermore, the relative age effect evident in soccer represents age and possibly maturational advantages compared to counterparts from others sports and the general population (Baxter-Jones, 1995).

Relationships between SA and numerous indicators of motor performance as speed, flexibility, explosive strength or power, muscular endurance ranged from low to moderate in children and adolescents (Beunen et al., 1978; Beunen & Malina, 1988; Lefevre Beunen, Steens, Claessens, & Renson, 1990; Malina et al., 2004). These studies identified static strength as positively associated with SA. In longitudinal approaches analysis with boys contrasting maturity status, early maturing obtained higher dynamic strength than late maturing at 11-17 ages (Malina et al., 2004).

Neural maturation and myelination of muscle nerves are not complete until sexual maturation is reached (Camic et al., 2010). Past literature examining the effects of maturation on isokinetic strength must be interpreted carefully once they derived maturational status from chronological age or have simply classified individuals as being either pre- or post- pubertal (De Ste Croix, Deighan, & Armstrong, 2003).

Blimkie (1993) summarizes the question of strength training in children and adolescents with a significant effect of strength training before puberty, although absolute gains are lower than those occurring in higher ages. The gains of strength at this stage (before puberty) will take place not by the increase in muscle mass, but as the increase in the levels of neuromuscular activation and the alteration of the contractile characteristics of the muscle. There were other studies that have been hypothesized that there was an association between testosterone and strength development (Round, Jones, Honour, & Nevill, 1999).

Mero, Jaakkola, and Komi (1990) found higher levels of testosterone activity in youth in pre-pubertal phase when subjected to a strength training program, thus advocating that the training stimulus would induce an increase in anabolic activity, which, for its part, it would increase the training of this physical quality, at least in the initial period of puberty. Ramos, Frontera, Llopart, and Feliciano (1998) have attempted to correlate endocrine function with changes in isokinetic muscle strength. They found a significant increase in testosterone with age in boys preceded the gains

in muscle strength, and, there was a moderate positive correlation between serum testosterone and isokinetic angle specific PT.

### Multilevel modelling

A longitudinal study can identify changes in motor performance (i.e. strength) or physiological functions and, for example, partition the relative contributions of training from those associated with growth and maturation. Multilevel modelling is appropriate for the analysis of longitudinal observations, (i.e. repeated measurements) (Goldstein, 1995). Multilevel modelling technique is an extension of multiple regression analysis and is adequate for analyzing hierarchically structured data.

Multilevel modelling investigation detects that the variance of the observations increases with time. These allow constructing individual slopes and intercepts and permits to determine the effects of each predictor variable on those individual slopes and intercepts and its significance can be determined by relating the observed effects to the respective change in standard errors (Baxter-Jones, Goldstein, & Helms, 1993). Thus, group effects larger than within-individual variation can be identified. Mixed longitudinal studies are suggested because information can be assessed over a shorter period, but such studies need to be carefully planned to include cohorts that overlap in time (Goldstein, 1979).

## **1.6. Rationale, objectives and outline of the Thesis**

Strength outputs, such as PT, are substantially correlated with body size descriptors and biological maturation (Malina et al., 2004) and are often expressed relative to size descriptors (total and appendicular). Ratio standards, however, are problematic, while the partitioning of inter-and intra-individual variation associated with age, maturation, size, and training is complex. Multiplicative allometric modeling has

been used to combine growth and maturation effects in cross-sectional analyses. Longitudinal developmental changes can also be modelled with static, ontogenetic and allometric multilevel analyses. Application of allometric multilevel modeling with young athletes is limited and did not consider the isokinetic strength assessment. Nevertheless, changes in conventional and functional combinations of torque values derived from the KF and KE using contrasting angular velocities at specific angle positions using gravity-corrected, windowed and filtered data are lacking in pediatric sports science.

Although there is some information on the strength relationships between the KF and KE for children and adolescents athletes, data on the age trends affecting these muscle groups are limited (De Ste Croix et al., 2003). There are few cross-sectional studies (De Ste Croix, Deighan, & Armstrong, 2007; Rouis, et al., 2015; Sliwowski, Grygorowicz, Wieczorek, & Jadcak, 2018) and even fewer longitudinal studies (Seger & Thorstensson 2000; De Ste Croix et al., 2002). Longitudinal or mixed longitudinal studies of growth and strength, with sufficiently large samples on youth athletes, are needed.

Therefore, the overall purpose of this thesis is to gain more understanding of the relationship between (the development of) strength and body size and composition and biological maturation, using a multidisciplinary approach. The current Thesis is presented in manuscripts format and is organized in **four sections**. The **first section** comprises a general introduction (Chapter 1) and methods (Chapter 2). **Chapter 2** provides an exhaustive description of the participants considered in different studies, well as the material, methods, and variables assessed. The quality control, different statistical techniques, and data interpretation are also described. The **second section** comprises the cross-sectional studies (study 1 and 2) and the **third section** the mixed-longitudinal studies (study 3, 4, and 5). The manuscripts that incorporate this Thesis have a common structure with minor adjustments according to the style of the journal where the manuscripts are submitted, either in the revision process or published.

The **second chapter** provides an exhaustive description of the participants considered in different studies, well as the material, methods, and variables assessed. The quality control, different statistical techniques, and data interpretation are also detailed described.

**Section 2** includes **chapter 3** (study 1) and **chapter 4** (study 2). Both consider adult athletes. Little is known when analyzing a wider spectrum of angular positions and not just the maximum point of the curve (i.e., PT). Due to its relevance and referred recognition it is important to better understand the technical assessment variation of the isokinetic dynamometer. It is also crucial interpreting accurate data from physiological movements of the knee that consider specific angles during the standardized range of motion. Test-to-test variation in isokinetic assessments was based on repeated tests within a period of 1-week.

Given the relatively limited data for youth athletes, in **Section 3**, longitudinal data are presented on adolescent male soccer players that have been followed across time (**Chapter 5 to 7; Study 3 to 5**). In the preceding context, these studies aimed to investigate the independent and interactive contributions of body size and composition, biological maturation to inter- and intra-individual development of knee joint (KF and KE) strength and to present allometric models.

Finally, **Section 4 (Chapter 8)** comprises the general discussion in which the findings of the various studies are summarized and put into context and their implications discussed.



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## **Chapter II**

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### **Methods**





## 2. Methods

### 2.1. Study design, place and sampling

All studies included in the present Thesis were conducted within projects partially funded by the Portuguese Foundation for Science and Technology (SFRH/BD/101083/2014), National Lottery Belgium (Nationale Loterij Belgie) and DEXIA Bank. These projects consisted of cross-sectional and mixed-longitudinal approaches conducted in accordance with ethical procedures of the Declaration of Helsinki for human studies by the World Medical Association Assembly (2014) and in accordance with ethical standards for sports medicine (Harriss, Macsween, & Atkinson, 2017).

Data collection was conducted using equipment from two different research units: 1) The Research Unit for Sport and Physical Activity, Faculty of Sport Sciences and Physical Education, University of Coimbra, Coimbra (uid/dtp/04213/2016) (study 1, 2 and 5); 2) The Department of Movement and Sports Sciences, Faculty of Medicine and Health Sciences, Ghent University, Gent, Belgium (study 3 and 4).

All participants and/or parents/legal guardians were recruited locally and volunteered to take part in the studies. Information about the objectives experimental protocol and procedures of the studies was provided. **Exclusion criteria:** history of Hamstrings, Quadriceps or knee injuries in the 12 months prior to muscle strength evaluation test. All participants were healthy with no history of musculoskeletal problems or injuries of the lower limbs. The written authorization of the participant and/or parents/legal was collected in a document, which contained all relevant information. Table 2.1 summarizes the basic characteristics of each study regarding design, sampling and variables.

**Table 2.1. Basic characteristics of each study.**

Study	Design	Sample	Age, years	Studied variables
1	Cross-sectional	26 athletes	18.6-33.9	Anthropometry; Training experience; Body composition (DXA); Dynamic (cc and ecc) strength parameters.
2	Cross-sectional	30 soccer players	20.0-35.7	Anthropometry; Training experience; Body composition (bioelectrical impedance); Dynamic (cc and ecc) strength parameters.
3	Mixed-longitudinal	67 soccer players	11.0-16.0	Biological (skeletal) age; Anthropometry; Body composition (skinfolds); Isometric strength parameters.
4	Mixed-longitudinal	67 soccer players	11.0-16.0	Biological (skeletal) age; Anthropometry; Body composition (skinfolds); Dynamic (cc) strength parameters.
5	Mixed-longitudinal	30 soccer players	12.0-14.0	Biological (skeletal) age; Training experience and volume; Anthropometry; Body composition (DXA); Dynamic (cc and ecc) strength parameters.

**Abbreviations:** DXA, Dual-energy X-ray Absorptiometry; cc, concentric; ecc eccentric.

## 2.2. Variables and measuring instruments

### Chronological age (CA)

CA was determined to the nearest 0.01 year by subtracting birth date from date of first testing measurement.

### Biological maturation (Skeletal age)

A posterior-anterior radiograph of the left hand-wrist was used to assess skeletal age (SA; Chapter 5-7). Chapter 5 and 6 films were rated using the Tanner-Whitehouse 2 method (TW2; Tanner, Whitehouse, Marshall, Healy, & Goldstein, 1975) and Chapter 7 using Fels method (Roche, Chumlea, & Thissen, 1988). The difference between SA and CA (SA minus CA) was used to classify players into maturity

categories: late (delayed), SA younger than CA by  $> 1.0$  yr; average (on time), SA  $\pm 1.0$  yr CA; early (advanced), SA older than CA by  $> 1.0$  yr; a SA was not assigned if the individual had attained skeletal maturity. The band of 1.0 year is consistent with age-specific standard deviations for SAs in adolescent boys and allows for errors associated with assessments (Malina et al., 2010).

### Anthropometry

A single experienced observer performed anthropometric assessments following standard procedures (Lohman, Roche, & Martorell, 1988).

**Stature and sitting height** were measured to the nearest 0.1cm with a Harpenden stadiometer (model 98.603, Holtain Ltd, Crosswell, UK and Harpenden sitting height table, model 98.607, Holtain Ltd, Crosswell, UK, respectively). All stature measurements were taken with the subject barefoot. The *Frankfort Plane* was considered as reference and indicates to the position of the head when the line joining the orbitale to the tragion is horizontal. The subjects stood erect ( $90^\circ$  at fossa poplitea and at the hip joint for sitting height) feet together against the stadiometer at a right angle to the mounted stadiometer. The heels, buttocks, upper back and cranium touched the stadiometer. The subjects heads were in the *Frankfort Plane*; arms relaxed at sides. The subjects were instructed to inhale and stretch up. The measurer slides the headboard of the stadiometer downed to the vertex and recorded the measurement.

**Body mass** was measured to the nearest 0.1kg using an electronic scale (SECA balance, model 770, Hanover, MD, USA). The subjects were weighed without shoes using lycra shims.

**Leg length** was estimated as stature minus sitting height. **Sitting height/stature ratio** (%) was also calculated in Chapter X (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002).

Intra-observer technical errors of measurement (TEM) for anthropometric measures were as follows (n=26): stature, 0.3cm; sitting height, 0.3cm; body mass, 0.2kg.

### Body composition

**Estimated fat and fat-free mass** (Chapter 5 and 6): Percentage body fat was estimated from skinfold thickness using the protocol of Parizkova (1977). Skinfolts (cheek, chin, thorax I and II, triceps, subscapular, abdomen, suprailiac, thigh, and calf) were evaluated using a Lange Caliper (Beta Technology, Ann Arbor, MI, USA). The original regression model was highly correlated ( $r=0.896$  for boys aged 9-12 and  $r=0.916$  for boys aged 13-16) with body density (hydrostatic weighting and estimation of residual air in the moment of weighting by the nitrogen dilution method). Intra-observer TEM: skinfolts sum, 0.5mm.

**Multi-frequency bioelectrical impedance analyzer** (InBody770; Biospace, Seoul, Korea) was used in Chapter 4 to estimate body composition. This analyzer processes 30 impedance measurements using six different frequencies (1, 5, 50, 250, 500, and 1000 kHz) at each of the five body segments (right and left upper arms, right and left legs, and trunk) and 15 reactance measurements using tetrapolar 8-point tactile electrodes at three different frequencies (5, 50, and 250 kHz) at each of the same five body segments. The total body impedance value was calculated by summing the segmental impedance values. It automatically displayed measurements of fat-free mass (FFM, kg), fat mass (FM, kg), and %FM. FFM was estimated from total body water (Lim et al., 2009). The measurement time was approximately 60 seconds; with the subjects in a standing position according to the manufacturer instructions after shoes, coats and sweaters had been removed.

### Dual-energy X-ray Absorptiometry (DXA)

It was used the DXA Lunar (DPX-MD +, Software: EnCORE version 4.00,145, GE Lunar Corporation, 726 Heartland Trail, Madison, WI 53717-1915 USA). A full body scanner was carried out, producing a report with the whole body, head, upper limbs, trunk (including pelvis, ribs, and spine), lower limbs information. Subsequently, in the processing phase, a region of interest preferred thigh was defined as described previously (Coelho-e-Silva et al., 2013; Tavares et al., 2016). For the whole body and each of the segments, the information includes bone mineral content and bone tissue area to subsequently determine the bone mineral density. DXA technology allows the determination of the fat tissue component and lean soft tissue (LST). The calibration was performed on the day before the first evaluated using the model (phantom) and the procedures recommended by the manufacturer.

### Isokinetic assessment

The isokinetic assessments were carried out in the preferred lower limb in a validated Biodex System 2 and System 3 dynamometers (Shirley, USA) (Pincivero, Lephart, & Karunakara, 1997; Drouin, Valovich-mcLeod, Shultz, Gansneder, & Perrin, 2004). The resolution and accuracy of the digital data provided by the standard computer systems are quite adequate for research purposes (Drouin et al., 2004). Dynamometer calibration was performed before the assessment session in accordance with the manufacturer's instructions (Biodex Medical Systems, Inc., 2000). Positioning was as follows: the chair was tilted back at 85° (hip flexion); straps were crossed over the trunk, pelvis, and the thigh of the preferred leg; the dynamometer axis of rotation was aligned to the external femoral condyle of the knee; the fixing strip of the pad was adjusted 2 centimeters above the upper edge of the fibular malleolus. The global range of movement was set at between 85-90°. Individual calibration of gravity was corrected prior to each test at the position of 30 degrees of knee flexion (Osternig 1986). In order to familiarize the participants and to eliminate the learning curve, before starting the test, and as recommended, specific 3-trial repetitions at the same

speed and action were performed (De Ste Croix, Deighan, Ratel, & Armstrong, 2009). During the test, participants were instructed to keep the arms crossed with the hands on the opposite shoulder (Brown, 2000). The screen of the computer linked to the dynamometer gave consistent real-time visual feedback (Baltzopoulos, Williams, & Brodie, 1991). The warm-up protocol consists of 5-minutes peddling in a cycle ergometer (814E Monark, Varberg, Sweden) with a resistance braking force corresponding to 2% of the body mass of the subject, cycling between 50 and 60 rpm (Brown, 2000). Reciprocal concentric (cc) and eccentric (ecc) muscular actions were tested considering 5 repetitions for each movement at  $60^{\circ} \cdot s^{-1}$  ( $1.05 \text{rad/s}$ ) and  $180^{\circ} \cdot s^{-1}$  ( $3.14 \text{rad/s}$ ). A 60-second interval was settled between the 3-repetition familiarization and the test (Perrin, 1993). For Chapter 3, 4 and 7 data, outputs were analyzed with the *Acqknowledge* software version 4.1 (Biopac Systems, Goleta, USA). Each individual curve was inspected in order to consider true isokinetic torques within 95% confidence interval of the angular velocity. The angle of the peak torque (PT) obtainment and PT value of the best from five repetitions were retained for analysis.

### Statistical analyses

According to the specific aim of each study, different statistical analyses were performed (Table 2.2.). Thus, different programs and instruments were used: IBM SPSS versions 23.0 and 24.0 software (Statistical Package for Social Sciences, SPSS, Chicago, USA), GraphPad Prism version 5.03 software (GraphPad Software, La Jolla, USA), MLwiN version 2.26 software (Centre for Multilevel Modelling; University of Bristol, UK) and *Acqknowledge* software version 4.1 (Biopac Systems, Goleta, USA). Alpha level was set at 0.05.

**Table 2.2. Statistical analysis used in each study.**

Analyses	Study				
	1	2	3	4	5
Kolmogorov-Smirnov normality test	✓	✓			
Paired samples <i>t</i> -tests	✓	✓			
Technical error of measurement (TEM)	✓				
Coefficients of variation (CV)	✓	✓			
Intra-class correlation coefficient (ICC)	✓	✓			
Cohen's <i>d</i> effect size	✓	✓			
Bland-Altman plot			✓		
Tolerance			✓	✓	✓
Variance inflation factor			✓	✓	✓
Multilevel modelling hierarchical REM			✓	✓	✓

**Abbreviations:** REM, random effects models.



## 2.3. References

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**Section**

**III**

**Cross-sectional Studies**

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## **Chapter III**

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### **Study 1**

**Reproducibility of isokinetic strength assessment of knee muscle actions in adult athletes: torques and antagonist-agonist ratios derived at the same angle position**



### **3. Reproducibility of isokinetic strength assessment of knee muscle actions in adult athletes: torques and antagonist-agonist ratios derived at the same angle position**

*Reference: Duarte, J. P. et al. (2018). Reproducibility of isokinetic strength assessment of knee muscle actions in adult athletes: Torques and antagonist-agonist ratios derived at the same angle position. PLoS One, 13(8), e0202261. doi: 10.1371/journal.pone.0202261*





### **3.1. Abstract**

The current study aimed to examine the reliability of the conventional and functional ratios derived from peak torques (PTs) and those obtained from the combination of knee flexors torque at the angle of knee extensors PT. Twenty-six male athletes (mean of  $24.0 \pm 0.7$  years) from different sports completed a test-to-test variation in isokinetic strength (Biodex, System 3) within a period of one week. Anthropometry and body composition assessed by Dual-energy X-ray Absorptiometry were also measured. The proposed isokinetic strength ratio measurements appeared to be highly reliable: conventional ratio at PT angle (intra-class correlation, ICC=0.98; 95% confidence interval; 95%CI: 0.95 to 0.99); functional extension ratio at PT angle (ICC=0.98; 95%CI: 0.96 to 0.99); and functional flexion ratio at PT angle (ICC=0.95; 95%CI: 0.89 to 0.98). Technical error of measurement (TEM) and associated percentage of the coefficient of variation (%CV) were as follows: conventional ratio at PT angle (TEM=0.02; %CV=4.1); functional extension ratio at PT angle (TEM=0.02; %CV=3.8); and, functional flexion ratio at PT angle (TEM=0.03; %CV=3.6). The current study demonstrated that the traditional and new obtained simple and combined isokinetic indicators seem highly reliable to assess muscle strength and function in adult male athletes. A single testing session seems to be sufficiently to obtain these isokinetic strength indicators.

**Keywords:** lower limb strength; knee joint stability; peak torque; angle-specific.



### **3.2. Introduction**

The terms muscle strength and muscle power are erroneously used as synonymous in many professional contexts. In the present study, the term ‘muscular strength’ refers to maximal muscular force in a single voluntary contraction (Knapik & Ramos, 1980). In the meantime, torque corresponds to the ability of a force to cause rotation on a lever. The relationship between the torque exerted by a muscle group and the range of motion of the joint is determined by mechanical characteristics of the anatomical lever system. In many muscle actions, such as knee extension and knee flexion, the mechanical disadvantage of the muscles occurs at the extremes of the range of motion. Isokinetic refers to dynamic muscular contraction characterized by a constant angular velocity of the movement (Thistle, Hislop, Moffroid, & Lowman, 1967; Baltzopoulos & Brodie, 1989). The angular velocity is kept constant by the dynamometer that adjusts the resistance applied to the muscles through the range of motion (i.e. the load applied to the muscle is increased at the point of highest mechanical advantage of the muscle and, correspondingly, the load is decreased at the extremes of the range of motion).

Several parameters are cited in the literature as a measure of isokinetic strength. Peak torque (PT) is consistently favored as the most prominent information retained for analysis (Thorstensson, 1976; Aagaard, Simonsen, Trolle, Bangsbo, & Klausen, 1994) and the angle of its occurrence is often reported (Kannus & Yasuda, 1992; Arnold, Perrin, & Hellwig, 1993; De Ste Croix, ElNagar, Iga, Ayala, & James, 2017). Meanwhile, mean torque corresponds to mean values of the moment of force during a particular range of motion. Additionally, and regarding the knee joint, the strength ratios tend to be calculated by dividing the maximal knee flexors (KF) moment by the maximal knee extensors (KE) moment measured at identical angular velocity and concentric (cc) or eccentric (ecc) contraction actions. In other words, the following ratio is usually termed as conventional ratio: KFcc:KEecc (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998). Two other ratios were also suggested to examine the antagonist-agonist strength relationship for knee extension and knee flexion actions. They were termed as functional extension ratio and

functional flexion ratio, respectively  $K_{Fecc}:K_{Ecc}$  and  $K_{Fcc}:K_{Eecc}$  (Aagaard et al., 1998). Active Quadriceps muscle contraction may create significant anterior tibial translation or shear and it may also produce substantial internal rotation of the tibia relative to the femur (Baratta et al., 1988; Draganich, Jaeger, & Kralj, 1989). The amount of co-activation of the hamstring muscles was suggested (More et al., 1993) to be crucial for ligamentous constraints, particularly the anterior cruciate ligament.

The conventional and functional ratios are being derived from the respective PTs that occurred at different angles for KE and KF. However, the antagonist-agonist strength relationship should be interpreted at the specific angle, particularly, at the angle of the agonist PT. Because of these data quality properties are of utmost importance in the evaluation of athletes, the purpose of the current study was to examine the reliability of the conventional and functional ratios derived from PTs and those obtained from the combination of KF torque at the angle of KE PT (the denominator in all composite variables).

### **3.3. Methods**

#### Procedures

The present study required repeated measurements with one week apart. The local Ethics Committee (CE/FCDEF-UC/00182016) previously approved the research project. Standards for research in sports medicine were followed taking into account the Declaration of Helsinki. Participants were informed about the objectives of the study, protocols and risks related to data collection. All provided written informed consent, which was approved by the ethics committee before the beginning of the study. Participants were informed that they could withdraw from the experiment at any time. Verbal consent was provided during the second test session to ensure voluntary participation. All measurements were performed at the Laboratory of Biokinetics at the Coimbra University Stadium and participants were instructed to avoid food ingestion for at least three hours before testing and not to drink caffeine

during the day. All assessments were performed at the same time of the day (09:00 - 12:00 a.m.).

### Participants

All participants were recruited in the Coimbra University Stadium according to the following inclusion criteria: males, aged >17 years and <36 years; 2+ years of training experience in competitive sports; none had any history of severe time-loss injury in the previous two months; none were taking any medication or supplements known to affect performance. Chronological age was determined to the nearest 0.01 year by subtracting birth date from date of first testing measurement. Training experience was obtained by questionnaire. The sample was composed of 26 adults aged 18.6-33.9 (mean of 24.0±0.7 years) with different training history [soccer (n=12), combat (n=4), swimming (n=3), rowing (n=2), track and field (n=1), tennis (n=1), volleyball (n=1), cycling (n=1), and roller hockey (n=1)]. Sample size was similar to previous studies aimed to examine the reproducibility of isokinetic and isometric knee extensor and flexor muscle strength (de Carvalho et al., 2013).

### Anthropometry

All measurements were obtained by a single experienced observer using standard procedures (Lohman Roche & Martorell, 1988). Body mass was assessed using a *SECA* portable scale (model 770, Hanover, MD, USA) with an accuracy of 0.1kg. Stature was measured using a *stadiometer Harpenden* (model 98.603, Holtain Ltd, Crosswell, UK) to the nearest 0.1cm. A portable table (Harpenden, model 98.607, Holtain Ltd, Crosswell, UK) was used to measure sitting height to the nearest 0.1cm. Leg length was estimated as stature minus sitting height.

### Body composition

Dual-energy X-ray Absorptiometry was used to assess body composition (Lunar DPX-MD+, Software: enCORE version 4.00.145, GE Lunar Corporation, Madison, WI, USA). All athletes were assessed in the supine position during a visit to a certified laboratory always performed during the mornings. An experienced technician supervised all assessments. The technology provides information regarding bone mineral content, bone mineral density, fat tissue and lean soft tissue. Extracted data for this study included information reporting whole body and lower limbs (preferred lower limb).

### Strength assessment

The protocol starts with a 5-min warm-up in a cycle ergometer (814E Monark, Varberg, Sweden) using a braking force corresponding to 2% of the body mass (Brown, 2000). The cadence was kept between 50 and 60 rpm. Afterwards, static stretching was done for the Quadriceps, Hamstrings and Adductors (20 seconds each position). Biodex System 3 dynamometer (Shirley, USA) was used to assess the isokinetic strength of KE and of the KF from the preferred lower limb at an angular velocity of  $60^{\circ}\cdot\text{s}^{-1}$ . This isokinetic dynamometer is a reliable and valid instrument (Drouin, Valovich-mcLeod, Shultz, Gansneder, & Perrin, 2004). Participants were seated in the dynamometer according to manufacture guidelines, that is, adopting a standardized position of  $85^{\circ}$  hip flexion from the anatomical position. The lever arm was aligned with the lateral epicondyle of the knee. The trunk, preferred thigh and leg (slightly above the medial malleolus) were stabilized with belts. Range of motion was defined for  $85^{\circ}$  degrees (knee flexion  $5^{\circ}$  to  $90^{\circ}$ ) as follows: athletes were asked to perform a voluntary maximal knee extension and the  $0^{\circ}$  was settled; afterwards, the initial 5 degrees of the flexion were completed and the dynamometer blocked. The reduction of the initial angles of the flexion was done to allow the athlete to exert at least 10% of the assigned torque limit. Prior to each test, individual calibration was completed for gravity correction (Osternig, 1986). This correction

was determined at the position of 30° of knee flexion. During the test, participants were instructed to keep the arms crossed with the hands on the opposite shoulder (Baltzopoulos, Williams, & Brodie, 1991). A specific 3-repetition trial was performed prior to each isokinetic test (De Ste Croix, Deighan, Ratel, & Armstrong, 2009), to reduce the effect termed “familiarization”. Finally, the test was completed with real-time visual feedback given by the screen of the dynamometer (Baltzopoulos et al., 1991). Reciprocal cc and ecc muscular actions were tested considering 5 repetitions for knee flexion and knee extension at 60°·s<sup>-1</sup> (1.05 rad·s<sup>-1</sup>). A 60-second interval was settled between the 3-repetition familiarization and the test (Perrin, 1993). The sequence was: 3-repetition knee extension cc combined with knee flexion cc; 60-second interval; 5-repetition knee extension cc combined with knee flexion cc; 60-second interval; 3-repetition knee extension ecc combined with knee flexion ecc; 60-second interval; 5-repetition knee extension ecc combined with knee flexion ecc. Data collection was obtained using a sampling rate of 100Hz and it was subsequently analyzed with the software *Acqknowledge*, version 4.1 (Biopac Systems, Goleta, USA). Each individual curve was inspected in order to consider true isokinetic torques within 95% confidence interval of the angular velocity of 60°·s<sup>-1</sup>. The angle of the PT and PT value of the best from five repetitions were retained for analysis (best curve performed by KE and KF in both the cc and ecc actions: KEcc, KEecc, KFcc, KFecc). Composite ratios were derived as follows:

$$\text{Conventional ratio} = \frac{PT_{KFcc}}{PT_{KEecc}} \quad (1)$$

$$\text{Functional extension ratio} = \frac{PT_{KFecc}}{PT_{KEecc}} \quad (2)$$

$$\text{Functional flexion ratio} = \frac{PT_{KFcc}}{PT_{KEecc}} \quad (3)$$

The above-presented ratios were independent of knee-joint angle. Therefore, the measurements of each muscle group were made at different angles. By using an



angular velocity of  $60^{\circ}\cdot\text{s}^{-1}$  and for a range of motion of  $85^{\circ}$ , the sampling rate of 100 Hz allowed data collection at specific angles. The torque (T) of the KFcc action and the T of the same KFecc action at the angle of the PT of the KEcc action were determined, respectively: T\_KFcc at angle PT\_KEcc and T\_KFecc at angle PT\_KEcc. Finally, the T of the KFcc action at the angle of the PT of the KEecc action was also determined (T\_KFcc at angle PT\_KEecc). T and PT values were expressed in Newton-meter (N·m). The following ratios were also possible:

$$\text{Angle\_specific conventional ratio} = \frac{\text{T\_KFcc at angle PT\_KEcc}}{\text{PT\_KEcc}} \quad (4)$$

$$\text{Angle\_specific functional extension ratio} = \frac{\text{T\_KFecc at angle PT\_KEcc}}{\text{PT\_KEcc}} \quad (5)$$

$$\text{Angle\_specific functional flexion ratio} = \frac{\text{T\_KFcc at angle PT\_KEecc}}{\text{PT\_KEecc}} \quad (6)$$

### Statistical analysis

Descriptive statistics (minimum, maximum, mean value, standard error of the mean, 95% confidence interval of the mean, and standard deviation) were calculated for chronological age, training experience and anthropometry. In addition, Kolmogorov-Smirnov test was used to check for normality. Comparisons between the type of sports were performed using *t*-test analysis. Means and standard deviations of PT, torque at specific angles, conventional and functional ratios were presented for each time-moment and intra-individual mean differences were examined using *t*-test analysis. Effect size was given by d-values of Cohen, which were interpreted as follows: <0.20 (trivial), 0.20 to 0.59 (small), 0.60 to 1.19 (moderate), 1.20 to 1.99 (large), 2.0 to 3.9 (very large), and  $\geq 4.0$  (extremely large) (Hopkins, Marshall, Batterham, & Hanin, 2009). Technical error of measurement (TEM), coefficients of variation (%CV) and intra-class correlation coefficient (ICC) were determined. ICC higher than 0.90 and CV lower than 10% are analytical goals commonly employed in sport and exercise science (Atkinson & Nevill, 1998), although recommendations

regarding CV in time trial protocols considers a more conservative percentage (<5%) (Currell & Jeukendrup, 2008). Additionally, the limits of agreement between ratios were examined by plotting the differences between time-moments relative to mean values of both assessments (Bland & Altman, 1986). Statistical significance was set at  $p < 0.05$  and all analyses were performed using the Statistical Package for the Social Sciences version 23.0 (Statistical Package for Social Sciences, SPSS, Chicago, USA) and GraphPad Prism version 5.03 software (GraphPad Software, La Jolla, USA).

### **3.4. Results**

Characteristics of the total sample are summarized in Table 3.1. All variables fit the assumption of normal distribution. Table 3.2 summarizes descriptive statistics by type of sports [i.e., team sports (soccer, volleyball and roller hockey) and individual sports (combat, swimming, rowing, track and field, tennis and cycling)] and includes results of comparisons between groups. Athletes of contrasting sports did not differ significantly in isokinetic parameters under analysis.

**Table 3.1. Descriptive statistics for the total sample (n=26) and test for normality assumption.**

Variable	Unit	Range		value	Mean		Standard deviation	(Kolmogorov-Smirnov)	
		minimum	maximum		SEM	(95% CI)		value	<i>p</i>
Chronological age	years	18.6	33.9	24.0	0.7	(22.6 to 25.5)	3.8	0.146	0.16
Training experience	years	2.0	25.0	13.5	1.1	(11.5 to 15.5)	5.6	0.118	0.20
Body mass	kg	58.4	89.2	74.2	1.6	(70.8 to 77.3)	8.4	0.110	0.20
Stature	cm	167.7	193.0	178.3	1.5	(175.1 to 181.1)	7.8	0.157	0.10
Estimated leg length	cm	76.5	94.6	85.0	1.1	(82.7 to 87.0)	5.4	0.088	0.20
Fat mass	%	7.3	30.3	15.3	1.2	(13.1 to 17.3)	6.2	0.135	0.20
Fat mass	kg	4.5	25.6	11.6	1.1	(9.4 to 13.8)	5.7	0.168	0.06
Fat-free mass	kg	51.4	70.5	61.9	1.1	(59.7 to 64.0)	5.6	0.117	0.20
Lower limb lean soft tissue	kg	8.5	11.9	10.4	0.2	(10.1 to 10.8)	0.9	0.152	0.12

**Abbreviations:** SEM, standard error of the mean; 95% CI, 95% confidence intervals.

**Table 3.2. Descriptive statistics (mean  $\pm$  standard deviation) by type of sports and comparisons between groups.**

Parameter	Time-moment	Muscle group	Action	Unit	Type of sports		Mean differences		Student t-test	
					Team sports (n=14)	Individual sports (n=12)	Value	(95% CI)	<i>t</i>	<i>p</i>
PT	M1	KE	cc	N·m	235.3 $\pm$ 41.5	212.4 $\pm$ 46.1	22.9	(-12.5 to 58.3)	1.334	0.40
PT	M2	KE	cc	N·m	232.7 $\pm$ 40.8	209.4 $\pm$ 43.7	23.3	(-11.0 to 57.5)	1.403	0.51
PT	M1	KF	ecc	N·m	268.8 $\pm$ 68.0	255.7 $\pm$ 61.1	13.1	(-39.6 to 65.8)	0.512	0.93
PT	M2	KF	ecc	N·m	270.3 $\pm$ 68.2	254.8 $\pm$ 60.4	15.5	(-37.0 to 68.1)	0.610	0.99
PT	M1	KF	cc	N·m	138.6 $\pm$ 23.9	125.8 $\pm$ 27.6	12.9	(-8.0 to 33.7)	1.274	0.54
PT	M2	KF	cc	N·m	136.8 $\pm$ 21.7	120.8 $\pm$ 27.9	16.0	(-4.0 to 36.1)	1.650	0.47
PT	M1	KE	ecc	N·m	161.7 $\pm$ 29.4	143.5 $\pm$ 30.9	18.2	(-6.3 to 42.6)	1.534	0.76
PT	M2	KE	ecc	N·m	163.5 $\pm$ 24.4	145.3 $\pm$ 29.0	18.2	(-3.4 to 39.9)	1.741	0.68
T at angle of PT_KEecc	M1	KF	cc	N·m	115.3 $\pm$ 18.9	102.8 $\pm$ 21.8	12.5	(-4.0 to 28.9)	1.559	0.28
T at angle of PT_KEecc	M2	KF	cc	N·m	112.8 $\pm$ 17.1	100.4 $\pm$ 20.8	12.5	(-2.9 to 27.8)	1.674	0.47
T at angle of PT_KEecc	M1	KF	ecc	N·m	120.5 $\pm$ 15.5	107.0 $\pm$ 18.5	13.5	(-0.2 to 27.3)	2.034	0.26
T at angle of PT_KEecc	M2	KF	ecc	N·m	121.0 $\pm$ 13.6	109.0 $\pm$ 19.9	12.0	(-1.6 to 25.6)	1.814	0.16
T at angle of PT_KEecc	M1	KF	cc	N·m	116.8 $\pm$ 22.0	103.7 $\pm$ 29.6	13.0	(-7.8 to 34.0)	1.291	0.36
T at angle of PT_KEecc	M2	KF	cc	N·m	116.4 $\pm$ 20.8	100.2 $\pm$ 26.0	16.1	(-2.8 to 35.1)	1.757	0.53

**Abbreviations:** 95% CI, 95% confidence intervals; PT, peak torque; T, torque; KE, knee extensors; KF, knee flexors; cc, concentric action; ecc, eccentric action; M1, time-moment 1; M2, time-moment 2.

Descriptive statistics for time-moment 1 and time-moment 2 are presented in Table 3.3, which also included intra-individual differences and results of the paired t-tests for all functional parameters: simple and combined variables. For the PT values, significant intra-individual differences were noted in the cc action of the KF ( $t=2.062$ ,  $p\leq 0.05$ ). However, the difference was interpreted as trivial. The inspection of torque values at specific angles noted a trivial but significant intra-individual difference for the cc action of the KF at the angle of the PT cc action of the KE ( $t=2.027$ ,  $p\leq 0.05$ ). With one exception differences are not significant for ratios. The mean values of intra-individual differences were significant for the functional extension ratio at the angle of the PT cc action of the KE ( $t=2.586$ ,  $p\leq 0.05$ , trivial).

**Table 3.3. Descriptive statistics (mean  $\pm$  standard deviation) by time-moment and intra-individual differences.**

Parameter	Muscle group	Action	Unit	Time-moment		Mean difference		Paired <i>t</i> -test		Magnitude effect	
				M1 (n=26)	M2 (n=26)	Value	(95% CI)	<i>t</i>	<i>p</i>	<i>d</i>	Qualitative
(a) PT	KE	cc	N·m	224.7 $\pm$ 44.3	222.0 $\pm$ 43.0	2.7	(-0.1 to 5.6)	2.001	0.06	0.06	trivial
(b) PT	KE	ecc	N·m	262.7 $\pm$ 64.0	263.1 $\pm$ 63.9	-0.4	(-5.1 to 4.3)	0.176	0.86	0.01	trivial
(c) PT	KF	cc	N·m	132.7 $\pm$ 26.0	129.4 $\pm$ 25.5	3.3	(0.1 to 6.6)	2.062	$\leq$ 0.05	0.13	trivial
(d) PT	KF	ecc	N·m	153.3 $\pm$ 30.9	155.1 $\pm$ 27.7	-1.8	(-6.4 to 2.8)	0.797	0.43	0.06	trivial
(e) T at angle of PT_KEcc	KF	cc	N·m	109.5 $\pm$ 20.9	107.1 $\pm$ 19.6	2.5	(-0.1 to 5.0)	2.027	$\leq$ 0.05	0.12	trivial
(f) T at angle of PT_KEcc	KF	ecc	N·m	114.3 $\pm$ 18.0	115.5 $\pm$ 17.5	-1.2	(-3.9 to 1.5)	0.920	0.37	0.07	trivial
(g) T at angle of PT_KEecc	KF	cc	N·m	110.8 $\pm$ 26.1	108.9 $\pm$ 24.3	1.8	(-0.9 to 4.6)	1.367	0.18	0.08	trivial
Conventional ratio	(c):(a)			0.60 $\pm$ 0.08	0.59 $\pm$ 0.08	0.01	(-0.01 to 0.02)	1.026	0.32	0.13	trivial
Conventional ratio at angle of PT_KEcc	(e):(a)			0.49 $\pm$ 0.07	0.49 $\pm$ 0.08	0.01	(-0.01 to 0.01)	1.420	0.17	0.01	trivial
Functional extension ratio	(d):(a)			0.69 $\pm$ 0.11	0.71 $\pm$ 0.10	-0.02	(-0.04 to 0.01)	1.911	0.07	0.19	trivial
Functional extension ratio at angle of PT_KEcc	(f):(a)			0.52 $\pm$ 0.09	0.53 $\pm$ 0.09	0.01	(-0.01 to 0.02)	2.586	$\leq$ 0.05	0.11	trivial
Functional flexion ratio	(c):(b)			0.53 $\pm$ 0.17	0.52 $\pm$ 0.16	0.01	(-0.01 to 0.03)	1.845	0.08	0.06	trivial
Functional flexion ratio at angle of PT_KEecc	(g):(b)			0.83 $\pm$ 0.10	0.84 $\pm$ 0.08	-0.01	(-0.02 to 0.01)	1.032	0.31	0.11	trivial

**Abbreviations:** M1, time-moment 1; M2, time-moment 2; 95% CI ,95% confidence interval; PT, peak torque; T, torque; KE; knee extensors; KF; knee flexors; cc, concentric; ecc, eccentric.

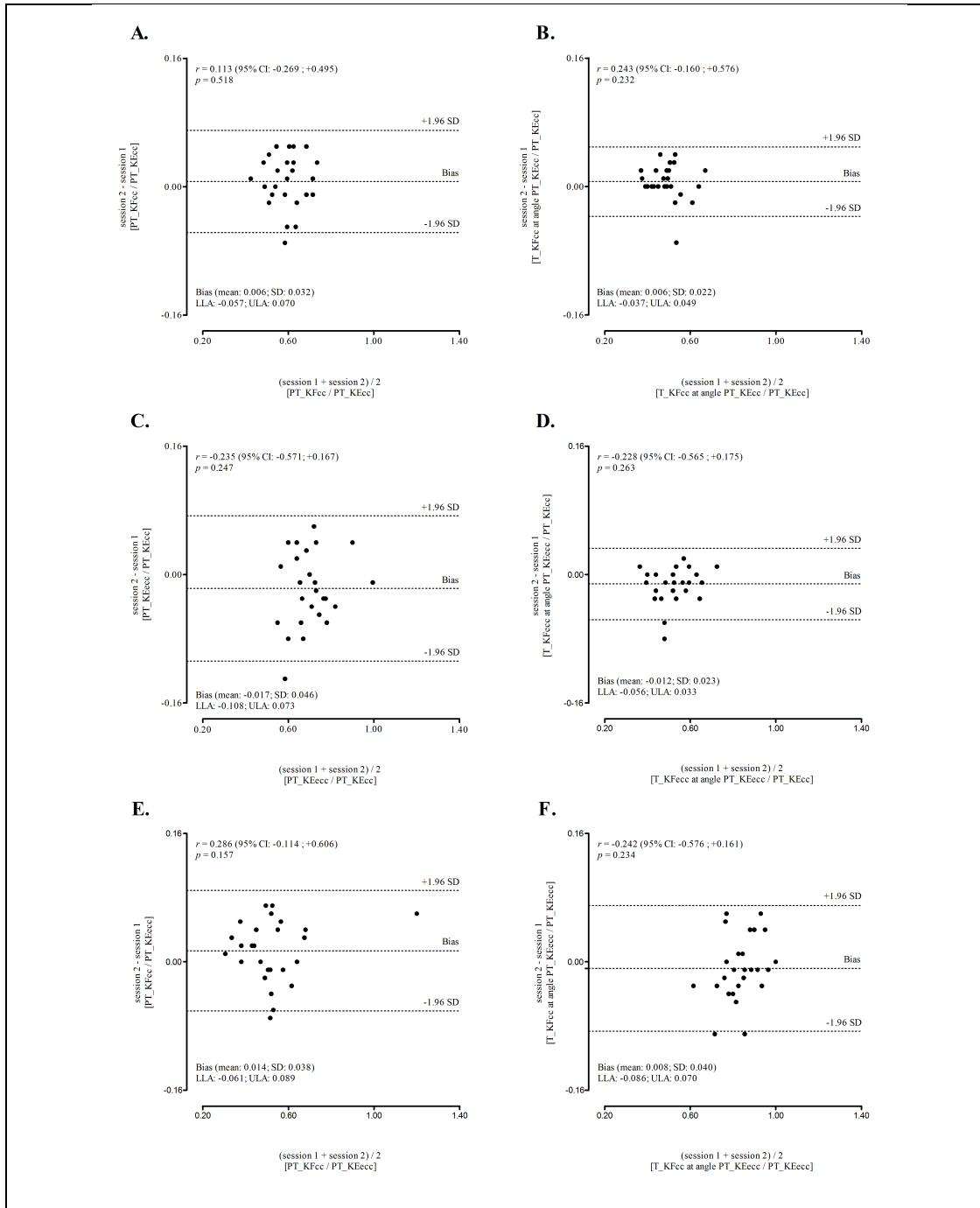
Table 3.4 reports the TEM and associated CV, which range between 2.33%-5.19% for PT value and 4.18%-4.46% for torque values at specific angles. Regarding composite variables, with one exception (functional flexion ratio from PTs obtained in different angles), all %CV were lower than 5% (3.36%-4.29%). The %CV for the functional ratio between PT of the cc action of the KF divided by the PT of the ecc action of the KE was 5.71%. For all measurements (simple and ratios) the ICC values were always over 0.95. Finally, Figure 3.1 illustrates the discrepancies of repeated measurement (Y-axes: session 2 minus session 1) for conventional ratio (panels A and B), for functional extension ratio (panels C and D) and for functional flexion ratios (panels E and F). The panels don't suggest heterocedasticity among axes (with X-axes being the mean of the repeated measurement) neither by visual inspection of the graphic nor based on statistics.

**Table 3.4. Technical error of measurements, coefficient of variation and intra-class correlation for the simple and combined variables.**

Parameter	Muscle group	Action	Unit	TEM	%CV	ICC	
						Coefficient	(95% CI)
(a) PT	KE	cc	N·m	5.2	2.33	0.993	(0.983 to 0.997)
(b) PT	KE	ecc	N·m	8.1	3.08	0.992	(0.981 to 0.996)
(c) PT	KF	cc	N·m	6.2	4.73	0.974	(0.942 to 0.988)
(d) PT	KF	ecc	N·m	8.0	5.19	0.961	(0.914 to 0.983)
(e) T at angle of PT_KEcc	KF	cc	N·m	4.6	4.25	0.976	(0.947 to 0.989)
(f) T at angle of PT_KEcc	KF	ecc	N·m	4.8	4.18	0.962	(0.916 to 0.983)
(g) T at angle of PT_KEecc	KF	cc	N·m	4.9	4.46	0.981	(0.958 to 0.992)
Conventional ratio	(c):(a)			0.02	3.36	0.956	(0.902 to 0.980)
Conventional ratio at angle of PT_KEcc	(e):(a)			0.02	4.08	0.978	(0.951 to 0.990)
Functional extension ratio	(d):(a)			0.03	4.29	0.950	(0.889 to 0.978)
Functional extension ratio at angle of PT_KEcc	(f):(a)			0.02	3.81	0.983	(0.962 to 0.992)
Functional flexion ratio	(c):(b)			0.03	5.71	0.987	(0.971 to 0.994)
Functional flexion ratio at angle of PT_KEecc	(g):(b)			0.03	3.59	0.948	(0.885 to 0.977)

**Abbreviations:** PT, peak torque; T, torque; KE, knee extensors; cc, concentric; ecc, eccentric; TEM, technical error of measurement; CV, coefficient of variation; ICC, intra-class correlation; 95% CI, 95% confidence interval.





**Figure 3.1. Agreement of repeated measures for isokinetic ratios: conventional ratio (PT\_KFcc:PT\_KEcc; Panel A), angle-specific conventional ratio (T\_KFcc at angle PT\_KEcc:PT\_KEcc; Panel B), functional extension ratio (PT\_KFcc:PT\_KEcc; Panel C), angle-specific functional extension ratio (T\_KFcc at angle PT\_KEcc:PT\_KEcc; Panel D), functional flexion ratio (PT\_KFcc:PT\_KEcc; Panel E), and angle-specific functional flexion ratio (T\_KFcc at angle PT\_KEcc:PT\_KEcc; Panel F).**

The relation between residuals (absolute mean differences between session 2 and session 1), the corresponding mean (heteroscedasticity diagnostic), and the 95% confidence intervals (95% CI) are also presented. The dashed lines represent 95% limits of agreement ( $\pm 1.96$  SD); lower limits of agreement (LLA) and upper limits of agreement (ULA).

### **3.5. Discussion**

The present research examined the reliability of traditional and new isokinetic simple and combined indicators, resulting from KE and KF measurements in maximal cc and ecc tests performed at  $60^{\circ}\cdot\text{s}^{-1}$ . The main results showed suitable levels of systematic bias, absolute and relative reliability for PT, torque at specific angles, conventional and functional ratios, and conventional and functional ratios at specific angles, recorded from 26 adult male athletes who were tested on two separate occasions, with an interval of one week. Allowing for sample size, type of sports did not seem to affect the parameters under analysis.

The presence of systematic bias was assessed using the paired t-test and the magnitude effect. The paired t-test was able to detect statistically significant differences only in three of the thirteen studied isokinetic indicators: PT of KF in the cc test (lower on retest), torque of KF at angle of PT of KE in the cc test (lower on retest), and functional extension ratio at angle of PT of KE in the cc test (higher on retest, due to a non-significant increased ecc angle-specific flexor torque and a non-significant decreased cc extensor PT). Learning effects (better on retest) or fatigue effects (worse on retest) are the most probable explanations for systematic bias (Atkinson & Nevill, 1998). However, a one-week interval between test sessions appears to be sufficient to recover from the previous test, although these differences were primarily for the flexor muscles, which are usually less accustomed to producing maximal levels of muscle strength. Nevertheless, ten of the thirteen-isokinetic indicators did not significantly differ between repeated time-moments and all magnitude effects were interpreted as trivial. Overall, the amount of systematic bias was acceptable. Lund et al. (2005) tested thirteen healthy participants (9 women, 5 men; mean age: 32 years; range: 18-55 years) in 5 time-moments using a Biodex System 3 dynamometer and found no systematic effect over time for knee extension and flexion performed at  $60^{\circ}\cdot\text{s}^{-1}$ .

The absolute reliability was verified using TEM and (%CV). Low TEM and CV below the proposed analytical goal of 5%, with the exception of the ecc knee

flexion PT (5.2%) and functional flexion ratio (5.7%), suggested relatively little within-subject variation. Nevertheless, it is likely that measurement errors between sessions might be more related to biological or mechanical variation (i.e. random error) (Atkinson & Nevill, 1998). In a study by Birmingham et al. (1998), a CV cut-off point of 8% resulted in correctly identification of 95% of maximal efforts.

The relative reliability was determined using the ICC. High ICCs for all the isokinetic indicators confirmed that the stability of the measurements over time was good. In general, the subjects maintained their position in the sample following the retest. Gleeson and Mercer (1996) suggested that  $CV < 6.1\%$  and  $ICCs \geq 0.88$  can be interpreted as suitable reliability in isokinetic strength testing. Lund et al. (2005) reported  $ICCs \geq 0.89$  for KEcc and KFcc PT across 5 time-moments. Feiring et al. (1990) also reported high ICCs for the KEcc (0.95) and KFcc (0.98) PT using a 7-days interval between testing sessions.

There is a lack of studies concerning the reliability of other isokinetic indicators, beyond the PT. Additionally, there are few studies that present results for KE and KF in cc and ecc actions using Biodex isokinetic dynamometers. Carvalho et al. (2011) presented higher CV and lower ICCs for KEcc (%CV=4.9-8.1; ICC=0.89-0.95), KFcc (%CV=3.9-16.5; ICC=0.78-0.99), KEecc (%CV=6.0-15.1; ICC=0.74-0.95) and KFecc (%CV=5.3-17.7; ICC=0.72-0.97) using a closely related methodology of isokinetic testing in adolescent basketball players. At  $60^\circ \cdot s^{-1}$ , Ayala et al. (2013) also presented higher CV and ICCs for KEcc (%CV=16.45; ICC=0.71), KFcc (%CV=13.33; ICC=0.78), KEecc (%CV=17.09; ICC=0.81) and KFecc (%CV=8.99; ICC=0.90) adopting a prone position.

The present study has several limitations that should be mentioned. The sample size was small, based on convenience and male subjects; therefore, the results are not generalizable. Further research in other populations is justified. Only two test sessions were considered; a third test session with an interval of one week could be more informative about the effect of familiarization between test sessions. Only the preferred lower limb was tested; further testing is necessary to assess the bilateral

differences. Only tests performed at  $60^{\circ}\cdot\text{s}^{-1}$  were used; further testing is necessary using other angular velocities, especially higher angular velocities when isokinetic dynamometers with higher sampling rates are available. The validity, responsiveness and clinical significance (especially relevant for subjects with knee injury) of the isokinetic indicators were not tested, issues that are lacking in the literature.

This information has practical implications in the management of research projects. Standardization of testing procedures is highly desirable, especially in terms of equipment calibration, warm-up procedures, familiarization training, number of submaximal trial repetitions, subject positioning and stabilization, axis alignment, testing setups, anatomical reference angle determination, verbal and/or visual feedback, gravity correction and testing protocol definition. Standardization of data collection, processing and analysis procedures are equally highly recommended.

### **3.6. Conclusions**

In summary, results evidenced that the traditional and new isokinetic simple and combined indicators considered in this study are reliable to assess muscle strength and function in adult male athletes when derived from an isokinetic dynamometer that provides sampling rates of at least 100Hz, using a closely related methodology. Isokinetic indicators obtained during a single testing session seem to be sufficiently reliable. This can be especially important when it is not possible to bring the athletes to the laboratory prior to the test session for familiarization purposes. In fact, isokinetic dynamometry is considered the gold standard for the objective measurement of dynamic muscle strength and function. Strategies to minimize measurement error are of extreme relevance. New and ground-breaking concepts and methods for reporting reliable isokinetic data must also be explored, for example, considering angle-specific information in a more specific and meaningful manner.

### 3.7. Acknowledgments

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### 3.8. References

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## **Chapter IV**

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### **Study 2**

**Angle-associated variation of functional and conventional ratios in  
soccer players**





## **4. Angle-associated variation of functional and conventional ratios in soccer player.**



#### 4.1. Abstract

The ability of the muscles to control the joint is influenced by the angular position. The main goal of our study was to compare the conventional and functional KF:KE during 85° knee range of motion knee at different knee angle positions (20°, 30°, 40°, 50°, 60° and 70° degrees of knee flexion). Thirty male (mean of 23.26±3.03 years) soccer players complete the study design. A subsample of ten soccer players completed a test-to-test variation in isokinetic strength (Biodex, System 3) within a period of one week. Anthropometry and body composition assessed by bioelectrical impedance were also measured. The proposed isokinetic strength KF:KE analysis appeared to be highly reliable: conventional KFcc:KEcc (ICC=0.760 to 0.852; %CV=1.4 to 6.9) and functional KFecc:KEcc (ICC=0.715 to 0.954; %CV=1.4 to 5.3). Results showed that both KF:KE values decreased with knee flexion movement. Comparison of KF:KE revealed differences between conventional and functional KF:KE, whereby magnitude effects suggested: large differences ( $d=1.22$ ) at 20°, moderate at 30°, 40°, 50° and 60° ( $d=0.95, 0.74, 0.61$  and  $0.64$ , respectively) and small ( $d=0.33$ ) at 70°. Current study methodology may be a useful tool to examine the role of antagonist co-activation for dynamic knee joint stability. When setting rehabilitation goals or screening high-risk soccer players, attention should be given to the athlete's specific strength curve profile.

**Keywords:** lower limb strength; knee joint stability; peak torque; angle-specific.



## **4.2. Introduction**

Muscle force is commonly assessed as peak torque during isometric, isokinetic, or isotonic muscle contractions (Aagaard et al., 1998). An isokinetic muscle action is defined by its performance at a constant angular velocity (Abernethy & Jurimae, 1996). In the current study, the maximum moment during an isokinetic movement in a single voluntary contraction (extension or flexion) was measured as an indicator of maximal muscular force applied in dynamic conditions (Knapik & Ramos, 1980). The isokinetic dynamometer is a reliable and valid instrument (Drouin, Valovich-mcLeod, Shultz, Gansneder, & Perrin, 2004) used in the last decades in different fields such as biomechanics, rehabilitation, conditioning, and research. Measuring voluntary maximum moments, angular velocity remains constant during extension and flexion movements with dynamometer giving a reaction force throughout the full range of joint motion (Cabri, 1991). This is clearly an advantage because the resistance that is offered by the dynamometer equalizes the individual's specific muscular capacity (Thistle et al., 1967), termed as accommodating resistance exercise.

Both isokinetic knee extension and flexion measurements are correlated with rapid and repeated knee movement during kicking (Kellis & Katis, 2007), showing the importance of this specific joint in soccer. A variety of outputs have commonly been used as the single peak moment or torque (PT) (Thorstensson, 1976; Aagaard et al., 1994), the moment at a specific knee joint angle (Kannus & Yasuda, 1992; Arnold, Perrin, & Hellwig, 1993; De Ste Croix et al., 2017) and KF:KE (Coombs & Garbutt, 2002; Evangelidis et al., 2015). The kinetic angular variable is expressed in N m or normalized to body mass as N m kg<sup>-1</sup>.

The majority of available studies consider specific knee flexors (KF) and knee extensors (KE) PT. However, this method lacks functional relevance, as it does not indicate angles. During concentric (cc) and eccentric (ecc) actions, KF and KE PT values occur around the mid-range of the movement (De Ste Croix et al., 2017), and muscle-specific torque generating capability is altered at extreme joint angles in

accelerating and decelerating phases of the movement (Komi, Linnamo, Silventoinen, & Sillanpaa, 2000). This erroneous method, of considering single PT values, represents an additional problem considering functional  $K_{Fecc}:K_{Ecc}$ , once concentric and eccentric PT will not necessarily occur at the same joint angle.

It's well known and described that during knee extension movement, the antagonistic eccentric action performed by Hamstrings co-activation decreases the anterior shift forces induced by the Quadriceps muscle group concentric action, and the opposite occurs in knee flexion movement (Senter & Hame, 2006). Despite this, available literature exploring the functional  $K_{Fecc}:K_{Ecc}$  is still lacking given the joint angle specific determination of the ratio importance. Therefore, the current study was aimed at comparing the conventional and functional ratios behavior throughout an interval of 10 degrees during the isokinetic range of motion (ROM) in the extension and flexion of the knee in adult soccer players.

### **4.3. Methods**

#### Procedures

Participants were evaluated in anthropometry, body composition and isokinetic dynamometry (Biodex System 3). The local Ethics Committee (CE/FCDEF-UC/00182016) previously approved the research project. Standards for research in sports medicine were followed taking into account the Declaration of Helsinki. Participants were informed about the objectives of the study, protocols and risks related to data collection. All provided written informed consent.

#### Participants

Thirty male soccer players (age:  $23.26 \pm 3.03$  years, body mass:  $77.5 \pm 8.6$ kg, stature:  $181.7 \pm 6.5$ cm) were recruited locally and volunteered to take part in this study. **Inclusion criteria:** (1) being a senior athlete (over than 18 years); (2) federated

competition soccer players; (3) soccer practice history for at least 8 years; (4) training at least 4 times and playing 1 game per week; (5) signing the informed consent declaration. **Exclusion criteria:** (1) history of Hamstrings, Quadriceps, traumatic or tendon knee injuries in the 12 months prior to muscle strength evaluation test. The soccer players were members of semi-professional clubs competing in the 3<sup>rd</sup> national league from Portugal, and had on average  $15 \pm 4$  years of experience in soccer practice and competition. They completed 4-5 soccer specific training sessions and usually a single match per week.

#### *Chronological age and training experience*

Chronological age (CA) was determined to the nearest 0.01 year by subtracting birth date from date of first testing measurement. Training experience was obtained by questionnaire and confirmed with soccer associations registers.

#### *Anthropometry*

A single and trained individual, using standardized procedures (Lohman, Roche, & Martorell, 1988), made all measurements. Body mass was obtained through a SECA (model 770, Hanover, MD, USA) with reduction of 0.1kg. The stature and sitting height were measured to the nearest 0.1cm, using a Harpenden stadiometer (model 98,603, Holtain Ltd., Crosswell, GB) and Harpenden sitting height table, respectively. The estimated leg length was calculated by the difference of the previous measures.

#### *Thigh volume*

Estimates of total thigh volume in the preferred leg were estimated from three circumferences and partial lengths. This technique divided the thigh into two segments, similar to truncated cones. Circumferences were measured at the gluteal furrow (proximal), mid-thigh (maximal) and above the patella (minimum). The lengths were measured between the transversal plans of consecutive circumferences.



Two skinfolds were measured to the nearest 0.01 mm with a Lange skinfold Caliper (Beta Technology, Santa Cruz, California, USA) on the front of the thigh, at the same level as mid-thigh circumference, and also at the posterior region. The volume of each truncated cone was calculated based on the Jones and Pearson (1969) equation and described in previous studies (Carvalho et al., 2012).

### Body composition

Body composition was measured using a valid, segmental, multi-frequency bioelectrical impedance analyzer (InBody770; Biospace, Seoul, Korea). This analyzer processes 30 impedance measurements using six different frequencies (1, 5, 50, 250, 500, and 1000 kHz) at each of the five body segments (right and left upper arms, right and left legs, and trunk) and 15 reactance measurements using tetrapolar 8-point tactile electrodes at three different frequencies (5, 50, and 250 kHz) at each of the same five body segments. The total body impedance value was calculated by summing the segmental impedance values. It automatically displayed measurements fat mass (FM). The measurement time was approximately 60 seconds; with the subjects in a standing position according to the manufacturer instructions after shoes, coats and sweaters had been removed.

### Strength assessment

Isokinetic assessment was carried out in the preferred lower limb in a validated Biodex System 3 dynamometer (Shirley, USA) (Drouin et al., 2004). Mechanical signals were recorded at a *sampling frequency* of 100 Hz. Biodex isokinetic System 3 includes 12- or 16-bit A/D converters resulting in a resolution of  $\approx 0.0244$  per cent of full scale. The resolution and accuracy of the digital data provided by the standard computer systems are quite adequate for research purposes (Drouin et al., 2004). Dynamometer calibration was performed before assessment session in accordance with the manufacturer's instructions (Biodex Medical Systems, Inc., 2000). Positioning was as follows: the chair was tilted back at 85° (hip flexion); straps were crossed over the trunk, pelvis, and the thigh of the preferred leg; the dynamometer

axis of rotation was aligned to the external femoral condyle of the knee; the fixing strip of the pad was adjusted 2 centimeters above the upper edge of the fibular malleolus. The global range of movement was set at 85°, with from 5° to 90° of flexion as follows: soccer players were asked to perform a voluntary maximal knee extension and the 0° was settled; afterwards, the initial 5 degrees of the flexion were completed and the dynamometer blocked. The reduction of the initial angles of the flexion was done to allow the athlete to exert at least 10% of the assigned torque limit. Individual calibration of gravity was corrected prior to each test at the position of 30 degrees of knee flexion (Osternig, 1986). In order to familiarize the soccer players and to attenuate the learning curve, before starting the test, and as recommended, specific 3-trial repetitions at the same speed and action were performed (De Ste Croix et al., 2009). During the test, participants were instructed to keep the arms crossed with the hands on the opposite shoulder (Brown, 2000). The screen of the computer linked to the dynamometer gave consistent real-time visual feedback (Baltzopoulos, Williams, & Brodie, 1991). The warm-up protocol consists of 5-minutes peddling in a cycle ergometer (814E Monark, Varberg, Sweden) with a resistance braking force corresponding to 2% of the body mass of the subject, cycling between 50 and 60 rpm (Brown, 2000). Reciprocal concentric (con) and eccentric (ecc) muscular actions were tested considering 5 repetitions for each movement at  $60^{\circ}\cdot s^{-1}$  ( $1.05\text{rad/s}$ ). A 60-second interval was settled between the 3-repetition familiarization and the test (Perrin, 1993). Outputs were analyzed with the *Acqknowledge* software version 4.1 (Biopac Systems, Goleta, USA). Each individual curve was inspected in order to consider true isokinetic torques within 95% confidence interval of the angular velocity of  $60^{\circ}\cdot s^{-1}$ . The angle of the PT obtainment and PT value of the best from five repetitions were retained for analysis (best curve performed by KE and KF in both the cc and ecc actions: KF<sub>ecc</sub>, KF<sub>ecc</sub>, KE<sub>ecc</sub>, KE<sub>cc</sub>). Composite ratios were derived as follows:

*Conventional ratio:*

$$PT_{KF_{cc}} : PT_{KE_{cc}} \quad (1)$$

*Functional ratio:*

$$PT\_KF_{ecc} : PT\_KE_{cc} \quad (2)$$

*Quality control*

A subsample of 10 soccer players was measured and tested on a second occasion within 1-week. Intra-individual differences for 20°, 30°, 40°, 50°, 60° and 70° of knee flexion positions ratio outputs are presented in Table 4.1. Analyzing %CV two values were above the critical value of 5%. Conventional KFcc:KEcc, %CV ranged between 1.4-6.9% and functional KFecc:KEcc between 1.4-5.3%. For all measurements the ICC values were always over 0.715. Values near full flexion angles presented lower ICC values. The lowest absolute reliability scores were found for those calculated at 60 and 70° for both conventional and functional KF:KE.

**Table 4.1. Test-retest reliability analysis (n=10).**

Angle	Conventional KF:KE				Functional KF:KE			
	Mean 1 (SEM)	Mean 2 (SEM)	%CV	ICC (95%CL)	Mean 1 (SEM)	Mean 2 (SEM)	%CV	ICC (95%CL)
20°	1.29 (0.09)	1.23 (0.13)	2.1	0.852 (0.402; 0.963)	1.63 (0.12)	1.68 (0.17)	1.4	0.954 (0.815; 0.089)
30°	1.12 (0.09)	0.97 (0.07)	6.9	0.827 (0.302; 0.957)	1.21 (0.12)	1.14 (0.10)	3.2	0.947 (0.787; 0.987)
40°	0.82 (0.07)	0.75 (0.05)	4.3	0.818 (0.267; 0.955)	0.83 (0.07)	0.89 (0.06)	3.2	0.892 (0.564; 0.973)
50°	0.63 (0.02)	0.58 (0.03)	4.4	0.850 (0.397; 0.963)	0.62 (0.04)	0.65 (0.04)	2.9	0.916 (0.660; 0.979)
60°	0.51 (0.02)	0.55 (0.03)	3.7	0.785 (0.133; 0.946)	0.50 (0.03)	0.56 (0.03)	5.3	0.715 (0.149; 0.929)
70°	0.45 (0.02)	0.44 (0.04)	1.4	0.760 (0.036; 0.940)	0.47 (0.04)	0.49 (0.05)	2.6	0.867 (0.465; 0.967)

**Abbreviations:** SEM, standard error of the mean; CV, coefficient of variation; ICC, intraclass correlation coefficient; CL, confidence limits

### Statistical analysis

All analyses were performed using the Statistical Package for the Social Sciences version 23.0 (Statistical Package for Social Sciences, SPSS, Chicago, USA) and figures obtained from GraphPad Prism version 5.03 software (GraphPad Software, La Jolla, USA). Kolmogorov-Smirnov test was used to check normal distribution. Intra-class correlation coefficients (ICC) were calculated for test-retest results. An ICC equal to or above 0.70 was considered acceptable (Hopkins, 2009). Test, means, standard deviations, and coefficients of variance (CV) were calculated. CV lowers than 5% are analytical goals commonly used in sport and exercise science (Atkinson, & Nevill, 1998; Currell, & Jeukendrup, 2008). Absolute reliability was assessed by paired-sample t-tests, to determine the differences between the test-retest sessions ( $p > 0.01$ ). The smallest worthwhile difference (SWD) was determined using the Cohen's  $d$  effect size (0.2 multiplied by the between-subjects SD). (Hopkins, Marshall, Batterham, & Hanin, 2009). Coefficients were interpreted as follows:  $< 0.20$  (trivial), 0.20 to 0.59 (small), 0.60 to 1.19 (moderate), 1.20 to 1.99 (large), 2.0 to 3.9 (very large), and  $\geq 4.0$  (extremely large). The results are presented as means  $\pm$  SD (standard error of the mean and 95% confidence intervals). The level of significance was established at  $p < 0.05$ .

## **4.4. Results**

Characteristics of the sample are summarized in Table 4.2. All variables fitted the assumption of normal distribution.

**Table 4.2. Descriptive statistics and test for normality assumption (n=30).**

Variable	Unit	Range		Mean			Standard deviation	(Kolmogorov-Smirnov)	
		Minimum	Maximum	Value	SEM	(95% CI)		Value	<i>p</i>
Chronological age	years	20.00	35.71	23.26	0.55	(22.33 to 24.43)	3.03	0.175	0.20
Training experience	years	9	28	15	1	(14 to 16)	4	0.118	0.20
Body mass	kg	59.0	94.2	77.5	1.6	(74.3 to 80.6)	8.6	0.096	0.20
Stature	cm	171.0	191.3	181.7	1.2	(179.6 to 184.0)	6.5	0.124	0.20
Estimated leg length	cm	78.3	94.2	86.2	0.7	(84.8 to 87.5)	4.0	0.135	0.17
Thigh volume	L	3.7	7.3	5.5	0.1	(5.2 to 5.8)	0.8	0.139	0.14
Fat mass	%	4.7	23.5	12.5	0.8	(10.7 to 14.1)	4.6	0.178	0.16
Fat mass	kg	3.3	19.9	9.9	0.8	(8.3 to 11.3)	4.1	0.154	0.68

**Abbreviations:** SEM, standard error of the mean; 95% CI, 95% confidence intervals.

Mean results between the two ratios differ in all angle positions (Table 4.3), however, are attenuated in near knee full flexion angular positions. These differences were considered to be large ( $d=1.22$ ) at 20°, moderate at 30°, 40°, 50° and 60° ( $d=0.95, 0.74, 0.61$  and  $0.64$ , respectively) and small ( $d=0.33$ ) at 70°.

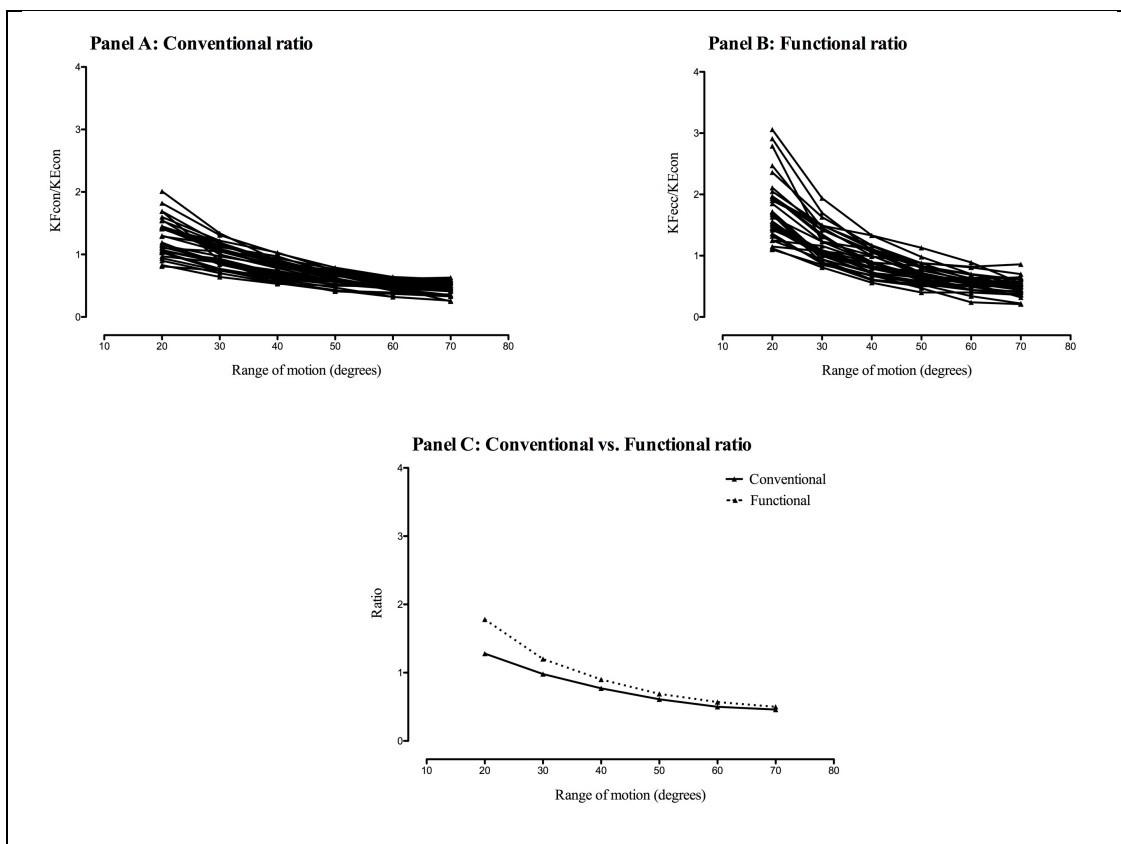
**Table 4.3. Comparative statistics and difference between ratios analysis with magnitude effect information (n=30).**

Angle	Conventional KF:KE		Functional KF:KE		Mean difference		Student t-test		Magnitude	
	Mean	Standard deviation	Mean	Standard deviation	value	(95% CI)	<i>t</i>	<i>p</i>	<i>d</i>	(qualitative)
20°	1.28	0.30	1.78	0.51	-0.50	(-0.67 to -0.34)	-6.177	0.001	1.22	large
30°	0.98	0.18	1.20	0.28	-0.22	(-0.31 to -0.13)	-4.844	0.001	0.95	moderate
40°	0.77	0.14	0.90	0.21	-0.13	(-0.20 to -0.07)	-4.281	0.001	0.74	moderate
50°	0.61	0.10	0.69	0.16	-0.08	(-0.13 to -0.04)	-3.652	0.001	0.61	moderate
60°	0.50	0.09	0.57	0.13	-0.07	(-0.10 to -0.02)	-3.323	0.002	0.64	moderate
70°	0.46	0.10	0.50	0.14	-0.04	(-0.09 to -0.01)	-2.079	0.047	0.33	small

Abbreviations: SEM, standard error of the mean; 95% CI, 95% confidence intervals.



Mean values and differences between ratios and muscle functions were verified according curve profiles (Figure 1). Graphic analyses of curves representing conventional and functional ratios presented lower values with knee flexion movement. Both ratios are larger in nearby full extension ratios (i.e. 20°), representing a disproportion between KF:KE, where Hamstrings reveal higher values for concentric and eccentric actions. Comparison of KF:KE revealed large to moderate differences between conventional and functional KF:KE, whereby the 20-40° range represented higher differences.



**Figure 4.1. Isokinetic strength profile of the knee joint throughout 20-70 degrees ROM. Panel A: KFcon:KEcon; Panel B: KFecc:KEecc; and Panel C: KFcon:KEcon vs. KFecc:KEecc.**

## **4.5. Discussion**

Previous research has indicated that functional KF:KE increases near to full knee extension (De Ste Croix et al., 2017). The aim of this study was to analyze isokinetic strength conventional and functional curve profiles (ROM between 20-70 degrees), in semi-professional soccer players, throughout knee extension and flexion. Conventional and functional KF:KE values in the preferred leg didn't present linear values. The main results reflect that curves of different ratios when analyzed with 10 degrees apart, although visually present the same tendency; they reveal statistically significant differences in terms of composite ratios. To our knowledge, this is the first study reporting isokinetic KF:KE using angle-specific ratios (20° to 70°) in adult soccer players.

Available studies examining the angle-specific KF:KE, use small sport independent sample sizes and do not all include joint angles near full knee extension (Aagaard, et al., 1998; Aagaard et al., 2000). Little is known when it parses a wider spectrum of angular positions throughout knee extension and flexion ROM, thus assessing knee flexors to extensors strength ratio at the same knee-joint angle may provide a more functionally relevant measurement. Angle-specific strength ratios could be calculated throughout the complete ROM (of knee extension:flexion). These curves have acceleration and decelerate phases; measurements at these knee-joint positions may be most relevant for hamstring strain injury. Current study provided moderate to large differences (Figure 4.1) (i.e., angles closer to extension show higher disparities than flexed angles) ratios derived from muscle function.

Usually the KF:KE are used to examine the similarity between agonist and antagonist muscle balance, moment velocity patterns and knee functional ability (Li et al., 1996). Several studies examined the aspect of conventional KFcc:KEcc (Osternig, 1986; Baltzopoulos & Brodie, 1989; Kannus, 1994). Values around 0.40 and 0.6 have been reported based on peak moments (Aagaard et al., 1995; Lehnert et al., 2014). This conventional KFcc:KEcc considers that measured action (concentric, eccentric or isometric) would take place simultaneously for both agonist and

antagonist and would be angle-independent (Baltzopoulos & Brodie, 1989). Subsequent studies examined functional KFecc:KEcc (Aagaard et al., 1996; Evangelidis et al., 2015; De Ste Croix et al., 2017). Physiological knee joint movement combines eccentric hamstring muscle contraction with Quadriceps concentric action during extension function (KFecc:KEcc) and the opposite in the act of knee flexion (KFcc:KEecc). A functional KFecc:KEcc of about 1.00 was stated (Aagaard et al., 1996). Low values (0.30) have been presented for functional KFcc:KEecc, representing knee flexion (Aagaard et al., 1996).

Soccer movement patterns that involve knee actions (i.e. cutting, landing, shooting) require hamstring eccentric contraction (Aagaard et al., 2000). This force magnitude represents a braking essential protection for knee stability. For example, near to complete knee extension, static stability is reduced and functional stability involves muscular control to protect the knee structures, and this reinforces the inappropriate use of using PT to calculate the KF:KE. By observing functional KFecc:KEcc functional (Figure 4.1) angle-specific curves, it is possible to interpret that eccentric hamstring muscle action is less effective in extended knee positions, and it is fair to assume that these positions represent a range where injury is most likely to occur (De Ste Croix et al., 2017). In the current study, the ROM considered for analysis was set between 20 and 70 degrees, considering only truly isokinetic outputs at  $60^{\circ} \cdot s^{-1}$  in a range of 10 degrees. Moment data outside this interval, representing accelerating and decelerating phases, should be discarded because of the lack of isokinetic conditions information and movement angular velocity (Evangelidis et al., 2015). In which concerns knee stability, during isokinetic and isometric actions, anterior cruciate ligament (ACL) is loaded in angles below 80 degrees and peak force occurs around 35-40° (Toutoungi, Lu, Leardini, Catani, & O'Connor, 2000). During knee flexion movements only posterior cruciate ligament (PCL) is in use. It is well documented that ACL rupture is most likely to occur near to full knee extension during a high velocity movement (De Ste Croix et al., 2017). Our findings demonstrate major imbalances in near full extension angles (20-30). This is attributed to lower KEcc torque production compared with KFecc torque production muscles as the knee extends.

Another important and relevant issue in soccer refers to muscular injuries. KF actions are required in maximal sprinting, kicking, braking or direction changes and sudden accelerations and decelerations (Ekstrand, Waldén, Häggglund, 2016). Imbalances in KF:KE may be due to the wide use of Quadriceps, mostly in concentric actions, performing repetitive kicks and passes (Ruas, Minozzo, Pinto, Brown, & Pinto, 2015). Without proper KF eccentric strength to decelerate these actions injury risk may be increased (Dallinga, Benjaminse, & Lemmink, 2012). Studies have pointed hamstring strains as being the 3<sup>rd</sup> most common soccer injury type, preceded by ankle and knee sprains (Ekstrand et al., 2016). Current study results are in accordance with recent literature in which considers peak concentric and eccentric torque, with these being more likely to occur in the range of 30-80° of knee flexion (De Ste Croix et al., 2017). Also it is well recognized that injury is likely to occur when the knee is closer to full extension (0-30°) (De Ste Croix et al., 2017).

It is well known that soccer players usually have a preferred leg for kicking, passing and controlling the ball (Capranica et al., 1992), however, the primary limitation of our study has to do with the evaluation of just one of the lower limbs. It is also suggested that KF:KE reported may have been influenced by external measurement variables such as age or training history (Holcomb, Rubley, Lee, & Guadagnoli, 2007). Thus, current study only controlled level, frequency and training time. Training load was not considered. Secondly, the current study did not consider nervous system activity measurement (EMG). Future research should contemplate the motor patterns activations of antagonist-agonist coordination.

#### **4.6. Practical implications**

Soccer player knee strength profile study may benefit trainers interpreting and thigh muscles imbalance. In particular, coaches and physical trainers should pay special attention to eccentric hamstring strength training to avoid lower-extremity injuries. Current study methodology may be a useful tool to examine the role of antagonist co-activation for dynamic knee joint stability. The findings of the current study

suggest that the ability of the muscles to control the joint is influenced by the angular position. Furthermore, it is recommend that, when setting rehabilitation goals or screening high-risk soccer players, attention should be given to the athlete's specific strength curve profile.

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## Section II KEY POINTS

Isokinetic dynamometry has become a favored method for the assessment of muscle function in both clinical research and sports science;

Muscle imbalances and particularly KF-to-KE imbalances have been widely suggested as potential risk factors for non-contact knee-joint injuries and Hamstring strains;

Muscle balance at the knee joint has typically been quantified by measuring the KF-to-KE peak torque (PT) ratio;

The antagonist-agonist strength relationship for knee extension and flexion may be better described by a functional KF:KE of eccentric Hamstring to concentric (cc) Quadriceps muscle strength and vice-versa;

Assessment of the knee flexors (KF) to extensors strength ratio at the same knee-joint angle provide a more functionally relevant measurement;

The ability of the muscles to control the joint is influenced by the angular position;

Functional ratios derived from angular positions near to full knee extension show higher disparities than flexed angles;

Eccentric (ecc) Hamstring muscle action is less effective in extended knee positions. These angular positions represent a range where the injury is most likely to occur.



**Section**

**III**

**Longitudinal Studies**

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## **Chapter V**

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### **Study 3**

#### **Developmental changes in isometric strength: longitudinal study in adolescent soccer players**



## **5. Developmental changes in isometric strength: longitudinal study in adolescent soccer players**

*Reference: Duarte, J. P. et al. (2018). Developmental Changes in Isometric Strength: Longitudinal Study in Adolescent Soccer Players. Int J Sports Med, 39(9), 688-695. doi: 10.1055/s-0044-100389*





## 5.1. Abstract

This study was aimed to examine longitudinal changes in isometric strength of the knee extensors (KEim) and knee flexors (KFim) at 30° and 60°. The sample was composed of 67 players aged 11.0-13.9 years at baseline over five years. Stature, body mass, skinfolds, and isometric strength (KEim30°, KFim30°, KEim60° and KFim60°) were measured. Fat mass and fat-free mass (FFM) were derived from skinfolds. Skeletal age was obtained using TW2 RUS. Multilevel random effects regression analyses extracted developmental polynomial models. An annual increment on chronological age (CA) corresponded to 5.6N (KEim30°), 2.7N (KFim30°), 4.6N (KEim60°) and 1.5N (KFim60°). An increment of 1kg in FFM predicted isometric strength as follows: 1.2N (KEim30°), 2.1N (KFim30°), 3.1N (KEim60°) and 2.0N (KFim60°). The following equations were obtained:  $KEim30^\circ = 5.759 \times CA + 1.163 \times FFM$ ;  $KFim30^\circ = -19.369 + 2.691 \times CA + 0.693 \times CA^2 + 2.108 \times FFM$ ;  $KEim60^\circ = 4.553 \times CA + 3.134 \times FFM$ ; and,  $KFim60^\circ = -19.669 + 1.544 \times CA + 2.033 \times FFM$ . Although skeletal maturity had a negligible effect on dependent variables, age and body size given by FFM were relevant longitudinal predictors. During adolescence, systematic assessment of knee extensors and knee flexors are strongly recommended to prevent imbalances of knee muscle groups.

**Keywords:** multilevel modeling; growth; skeletal maturation; youth athletes.



## **5.2. Introduction**

Movements in soccer involve short, intense and repeated episodes of activity including rapid changes of direction, accelerations or jumps (Mohr, Krstrup, & Bangsbo, 2003). Computerized time-motion analyses evidenced that top-class players performed higher-intensity runs during a game than moderate professional players (Mohr, Krstrup, & Bangsbo, 2003). Moreover, available literature also suggested a relationship between single sprint performances, repeated sprints with strength of the knee extensors and flexors among 38 adult soccer and rugby players (Newman, Tarpinning, & Marino, 2004). Knee muscles strength is commonly measured as the maximal force generated or moments of force produced (in N and N m, respectively) during a voluntary contraction under standardized conditions (Sale, 1991). In that particular, isokinetic dynamometry provides information regarding muscular contraction when the velocity of the movement is controlled (Gleeson & Mercer, 1996).

Age- and maturity-associated variations in the functional capacities are well documented both in school children and adolescents (Malina, Bouchard, & Bar-Or, 2004a) and in youth soccer (Malina, Eisenmann, Cumming, Ribeiro, & Aroso, 2004b) although available data are mainly cross-sectional (Malina et al., 2004b; Figueiredo, Goncalves, Coelho-e-Silva, & Malina, 2009). A recent study reported the contributions of chronological age (CA), anthropometry, motor coordination and flexibility to explosive power of youth soccer players (Deprez et al., 2015). In contrast, the influence of maturity-associated variation on isokinetic and isometric strength has received little attention in the general population (De Ste Croix, Deighan, & Armstrong, 2003) and in samples of youth soccer athletes, particularly. Previous studies have indicated that strength increases with age (Malina et al., 2004a), but the mechanisms associated with this increase require further investigation. Cross-sectional data evidenced that age-related increases in knee muscle functions for a sample of young wrestlers (n=135; CA: 11.1-18.2 years) could not be accounted by changes in body size given by stature and body mass, and authors hypothesized maturation as another potential determinant of strength (Camic

et al., 2010). Limited observations on adolescent male soccer players suggested an independent effect of self-reported stage of sexual maturation on isokinetic strength of the knee extension and knee flexion (Forbes et al., 2009). Meantime, literature suggested that maturation was a non-significant contributor to explain intra and inter-individual variability in strength once stature and body mass are accounted for (De Ste Croix et al., 2003).

The current study was aimed to examine developmental changes in isometric strength outputs of the knee flexors and knee extensors at different angular positions in a mixed-longitudinal sample of youth soccer players aged 11.0-13.9 years at baseline. It was hypothesized that biological maturation and muscularity were relevant longitudinal predictors of isometric muscle strength.

### **5.3. Methods**

#### *Procedures*

Clubs from the provinces East-Flanders and West-Flanders were contacted by the research leader of the Ghent Youth Soccer Project (Vaeyens et al., 2006). Clubs represented all competition levels (local to elite). The study adopted a mixed-longitudinal design. The cohorts ranged between 11.0 and 13.9 years of age at baseline. Measurements were performed over five years. Therefore, it was possible to estimate a consecutive developmental trend (11.0-16.9 years). The study was conducted in accordance with established ethical procedures for sports medicine (Harriss, Macsween, & Atkinson, 2017) and approved by Ethics Committee of Ghent University Hospital (Vaeyens et al., 2006). Informed written consent was individually obtained from parents or legal guardians. Participants were informed that participation was voluntary and that they could withdraw from the study at any time. Adolescent players were instructed not to eat and drink coffee or substances containing caffeine at least 3 hours before testing sessions. Assessments were performed after school hours at the same day period time (3.00-6.00 p.m.). All tests

were completed within a single week. An initial testing session was used for anthropometry and laboratory assessment and a second session to visit hospital for the X-ray exam needed for the determination of skeletal age (SA).

### Participants

The final sample comprised 67 Flemish male soccer players. Participants were retained for analyses when complete anthropometry, SA and isometric data were assessed more than two occasions. The numbers of participants per time-moment by CA groups is summarized in Table 5.1. The median number of observations per subject was four. About 17% were measured on all five occasions. Players were categorized by competitive level as mentioned elsewhere (Vaeyens et al., 2006). Participants were assigned to one of three subgroups according to competitive level. Elite players (n=15) were engaged in youth teams of first (highest) or second division clubs and practiced 6-7 hours per week (~4 training sessions and one game at the weekends). Sub-elite players (n=23) were involved in clubs that compete on third or fourth divisions and trained 4-5 hours per week (~3 training sessions plus one game at the weekend). Non-elite players (n=29) were part of clubs that participated on regional championships and trained 3-4 hours per week (usually two training sessions and one game per week).

**Table 5.1. Number of participants per measurement occasion and chronological age group.**

Age groups (years)	Time-moments					Total number of measurements
	1	2	3	4	5	
11.0-11.9	23	6				29
12.0-12.9	37	25	6			68
13.0-13.9	7	32	24	2		65
14.0-14.9		5	32	16	3	56
15.0-15.9			2	27	16	45
16.0-16.9				3	24	27
Total	67	68	64	48	43	290

### Age and skeletal maturity

Hand-wrist radiographs of the left hand were obtained in a clinic. A single trained physician assessed SA using the TW2 RUS protocol (Tanner, Whitehouse, Marshall, & Healy, 1975). The difference between SA and CA (SA minus CA) was used to classify the maturity status as follows: late, SA younger than CA by  $> 1.0$  year; average, SA within  $\pm 1.0$  year of CA; or early, SA older than CA by  $> 1.0$  year (Malina, 2011). An SA was not assigned if the player had attained skeletal maturity.

### Anthropometry (including estimates of body composition)

Stature and body mass were measured to the nearest 0.1cm and 0.1kg, respectively, using a stadiometer (Harpenden 98.603, Holtain Ltd, Crosswell, UK) and a scale (SECA 770, Hanover, MD, USA). Determination of fat mass (in percentage) was obtained from 10 skinfolds (cheek, chin, thorax I and II, triceps, subscapular, abdomen, suprailiac, thigh and calf) (Parizkova, 1977) using a Lange Caliper (Beta Technology, Ann Arbor, MI, USA). Fat mass and fat-free mass (FFM) were derived (Forbes et al., 2009). Intra-observer technical errors of measurement (TEM) for anthropometric measures were as follows: stature, 0.3cm; body mass, 0.2kg; and, skinfolds sum, 0.5mm.

### Isometric strength assessment

The same technician administered all tests and provided verbal instructions. Strength testing was performed on the preferred lower limb using a standardized protocol (De Ste Croix et al., 2003). Each participant performed a 5-min cycling warm-up on a Monark cycle ergometer (Monark 814E, Varberg, Sweden) with 2% of body mass as resistance at 60 rpm, and three 20-s bouts of static stretching (Brown, 2000). The subject was then positioned in the dynamometer (BIODEX System 2, Shirley, USA). Gravity correction and adjustment size were adequately done following recommendations by the manufacturer (Osternig, 1986). The preferred leg was positioned at 30° and 60° of knee flexion, in accordance with previous studies

(Pincivero, Gear, & Sterner, 2001; de Vasconcelos et al., 2009; Krishnan, Allen, & Williams, 2011). The angular position of the knee was defined with zero corresponding to maximum limit of the knee extension. Three 5-second maximal voluntary isometric contractions were performed by the knee extensors and knee flexors at each angular position (De Ste Croix et al., 2003). Verbal encouragement was provided as recommended (Baltzopoulos & Kellis, 1998). For each angular position, the highest isometric strength values of the knee extensors (KEim30° and KEim60°) and knee flexors (KFim30° and KFim60°) were retained for subsequent analysis. Afterwards, KFim:KEim ratios at 30° and 60° positions were calculated (Oberge, Moller, Gillquist, & Ekstrand, 1986; Akagi, Tohdoh, & Takahashi, 2014). Repeated measurements for isometric strength were not obtained in the Ghent Youth Soccer Project. However, pairwise coefficients of variation between test-retest sessions [ $100 \times \text{TEM} / ((\text{mean moment 1} + \text{mean moment 2}) / 2)$ ] for a subsample of 26 athletes for peak torque of KE and KF in concentric and eccentric actions ranged from 3.1% to 5.2%. The corresponding intra-class correlation coefficients [(1.1); one way random, single measure] ranged 0.961-0.993.

### Statistical analysis

Means and standard deviations were determined for the total sample by age groups (11-16 years). A multilevel modeling approach using hierarchical random effects models (REM) was used (Baxter-Jones & Mirwald, 2004) based on a specific statistical package (MLwiN v2.26, Center for Multilevel Modelling, University of Bristol, Bristol, UK). Two levels were considered: level 1 corresponded to within-individual variation; level 2 referred to between-individuals variation. The additive polynomial multilevel model was used to summarize the developmental changes on KFim and KEim at 30° and 60°:

$$y_{ij} = (\alpha + \mu_j) + (\beta + \nu_j)\chi_{ij} + (z_{1ij} + z_{2ij} + \dots + z_{nij}) + \varepsilon_{ij} \quad (1)$$

CA ( $x$ ) was included in both the fixed and random parts of the model, which is apparent when equation 1 is re-arranged into fixed and random components:



$$y_{ij} = (\alpha + \beta_j \chi_{ij}) + (z_{1ij} + z_{2ij} + \dots + z_{nij}) + (\mu_j + \nu_j \chi_{ij} + \varepsilon_{ij}) \quad (2)$$

where  $y$  was the KEim30° (N), KFim30° (N), KEim60° (N) or KFim60° (N) peak torques on measurement occasion  $i$  in the  $j$ th individual,  $\alpha$  was the constant for each  $j$ th individual,  $\beta_j \chi_{ij}$  was the slope for the peak torques over time for the  $j$ th individual. Chronological age (time-dependent variable) was centered around its mean value of 13.83 years to shift the origin of the explanatory variables (Rasbash et al., 1999).  $z_1$  to  $z_n$  were the coefficients of explanatory variables (CA, stature, FFM) at assessment occasion  $i$  in the  $j$ th individual (Baxter-Jones, Goldstein, & Helms, 1993). These were the fixed parameters in the model. Random parameters in the model were  $\mu_j$ ,  $\nu_j \chi_{ij}$  and  $\varepsilon_{ij}$ . It was assumed that they were independent and fitted normal distribution assumptions, with means equal to zero and variance  $\sigma^2$ .  $\varepsilon_{ij} \sim N[0, \text{var}(\varepsilon_{ij})]$  was the level 1 residual (within-individual variance) for the  $i$ th assessment of KEim30° (N), KFim30° (N), KEim60° (N) or KFim60° (N) peak torques in the  $j$ th individual.  $\mu_j \sim N[0, \text{var}(\mu)]$  was the between-individuals intercept variance and  $\nu_j \chi_{ij} \sim N[0, \text{var}(\nu_j \chi_{ij})]$  was the between-individuals slope variance; they were interpreted as level 2 residual (between subjects) variances for the  $j$ th individual. The equation  $\mu_j \times \nu_j \chi_{ij} \sim N[0, \text{var}(\mu_j \times \nu_j \chi_{ij})]$  explained the intercept-slope covariance relationships among the intercepts and slopes in the model (Baxter-Jones & Mirwald, 2004).

A stepwise procedure was adopted, i.e. predictor variables ( $z$  fixed effects) were added one at a time, and likelihood ratio statistics were used to judge the statistical fit of the model (Rasbash et al., 1999). Predictors ( $z$ ) were accepted as significant if the estimated mean coefficient was greater than twice the standard error of the estimate; if the criterion was not attained, the predictor was discarded. CA power functions (centered  $CA^2$ ) were introduced into the linear models to allow for the nonlinearity of KEim30° (N), KFim30° (N), KEim60° (N) or KFim60° (N) peak torque development. Based on analytical [i.e. Pearson's product moment correlations ( $r_{y,x}$ ) between performance parameters ( $y$ ) and potential predictors ( $x$ ) at baseline and measurement occasions 2, 3, 4, 5] and biological assumptions, the following variables were considered in the multilevel models: centered CA, centered  $CA^2$ ,

skeletal maturity status (average vs. late and early vs. late), stature and FFM. A tolerance  $> 0.10$  and a variance inflation factor  $< 10$  were set to avoid collinearity between explanatory variables (Slinker & Glantz, 1985). Comparisons of the multilevel model structures (KEim30°, KFim30°, KEim60° and KFim60°) were based on the Akaike (1974) information criterion:  $-2 \log \text{likelihood} + 2 \text{ number of parameter fitted}$ . To determine the accuracy of the equations, the obtained models to estimate KEim30°, KFim30°, KEim60° and KFim60° were tested using a random selection of one-half of the original sample. Statistical differences between real and predicted scores were initially examined using paired sample *t*-tests. Subsequently, data were visually inspected using Bland-Altman plots (Bland & Altman, 1986) that combined the errors against the mean derived from real and estimated values (data not-shown). Heteroscedasticity was examined by calculating the correlation coefficients between the absolute differences corresponding mean (Nevill & Atkinson, 1997) using GraphPad Prism version 5.03 software (GraphPad Software, La Jolla, USA). Alpha level was set at 0.05.

## **5.4. Results**

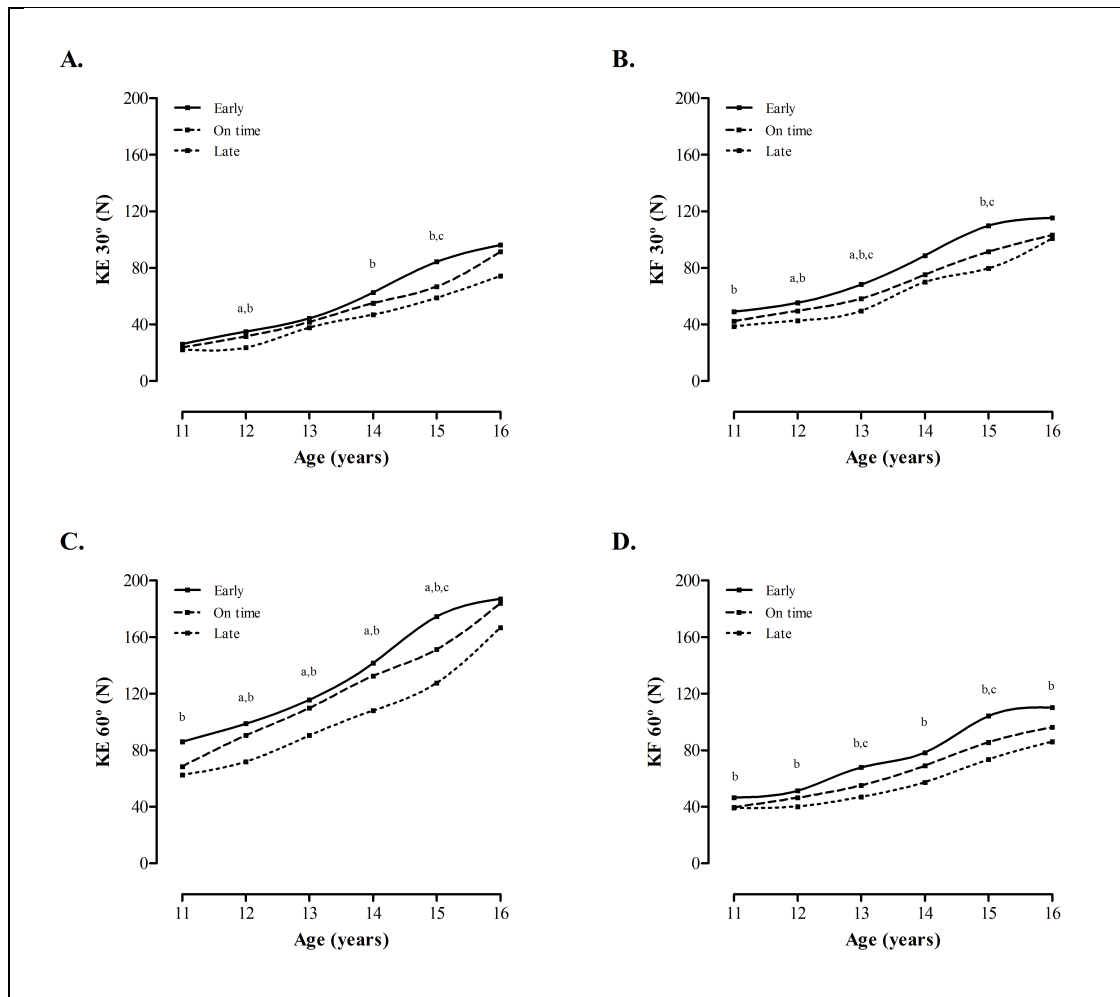
Descriptive statistics are summarized, by age group, in Table 5.2. As expected, stature, body mass and strength increased with CA. On average, estimated fat mass increased, while % Fat declined from 17.1% at 11 years of age to 14.5-14.8% at ages 15 and 16 years. Estimated gains in isometric strength from 11 to 16 years were apparent. Mean values increased approximately 57N and 100N, which corresponded to 223% and 134% of the mean at baseline respectively for KEim30° and KEim60°. For KFim30° and KFim60° the absolute and relative gains were respectively 61N (139%) and 56N (136%). Regarding ratio analyses at 30° position the mean values tended to fluctuate from 1.68-1.75 at younger ages to 1.37-1.51 at older ages. At 60° position the conventional ratio remained relatively stable with mean scores ranging between 0.54 and 0.59.

**Table 5.2. Descriptive statistics (mean  $\pm$  standard deviation) and frequencies by age group considering all measurements (n=290).**

Variable	Unit	11 years (n=29)	12 years (n=68)	13 years (n=65)	14 years (n=56)	15 years (n=45)	16 years (n=27)
Chronological age	(years)	11.44 $\pm$ 0.39	12.52 $\pm$ 0.30	13.43 $\pm$ 0.30	14.45 $\pm$ 0.27	15.53 $\pm$ 0.29	16.52 $\pm$ 0.36
Skeletal age	(years)	11.94 $\pm$ 1.11	12.71 $\pm$ 1.45	13.70 $\pm$ 1.14	14.68 $\pm$ 1.11	15.99 $\pm$ 1.08	16.98 $\pm$ 1.08
SA/CA	(years)	1.04 $\pm$ 0.09	1.02 $\pm$ 0.11	1.02 $\pm$ 0.09	1.02 $\pm$ 0.08	1.03 $\pm$ 0.07	1.03 $\pm$ 0.07
SA-CA	(years)	0.50 $\pm$ 1.01	0.19 $\pm$ 1.43	0.27 $\pm$ 1.14	0.23 $\pm$ 1.16	0.46 $\pm$ 1.13	0.46 $\pm$ 1.09
Skeletal maturity status							
Late	(f)	9	22	19	12	13	13
On time	(f)	17	34	35	36	27	10
Early	(f)	3	12	11	8	5	4
Stature	(cm)	147.2 $\pm$ 5.8	152.1 $\pm$ 7.6	159.6 $\pm$ 8.3	167.0 $\pm$ 8.3	172.8 $\pm$ 7.6	177.2 $\pm$ 7.7
Body mass	(kg)	37.1 $\pm$ 6.3	40.6 $\pm$ 7.4	46.9 $\pm$ 8.8	52.8 $\pm$ 10.4	59.2 $\pm$ 8.9	62.8 $\pm$ 8.1
Fat mass	(%)	17.1 $\pm$ 4.9	15.9 $\pm$ 3.7	15.9 $\pm$ 4.5	15.5 $\pm$ 4.3	14.5 $\pm$ 3.0	14.8 $\pm$ 2.3
	(kg)	6.5 $\pm$ 2.9	6.7 $\pm$ 2.8	7.6 $\pm$ 3.4	8.4 $\pm$ 3.8	8.8 $\pm$ 3.0	9.4 $\pm$ 2.2
Fat-free mass	(kg)	30.6 $\pm$ 4.0	33.8 $\pm$ 5.3	39.3 $\pm$ 6.3	44.4 $\pm$ 7.6	50.4 $\pm$ 6.5	53.5 $\pm$ 6.7
Isometric at 30°							
KE	(N)	25.5 $\pm$ 6.8	31.1 $\pm$ 8.6	42.1 $\pm$ 14.0	56.2 $\pm$ 17.7	70.0 $\pm$ 17.9	82.3 $\pm$ 31.0
KF	(N)	43.7 $\pm$ 11.0	50.1 $\pm$ 12.9	60.0 $\pm$ 18.7	78.6 $\pm$ 26.1	94.1 $\pm$ 27.9	104.5 $\pm$ 32.2
KF:KE	(N:N)	1.75 $\pm$ 0.43	1.68 $\pm$ 0.43	1.57 $\pm$ 0.88	1.51 $\pm$ 0.82	1.37 $\pm$ 0.32	1.51 $\pm$ 1.03
Isometric at 60°							
KE	(N)	74.7 $\pm$ 19.6	88.3 $\pm$ 22.5	107.2 $\pm$ 27.5	132.2 $\pm$ 34.4	152.7 $\pm$ 34.9	174.5 $\pm$ 48.7
KF	(N)	41.3 $\pm$ 8.8	47.1 $\pm$ 12.8	57.7 $\pm$ 19.6	70.9 $\pm$ 22.3	88.9 $\pm$ 25.6	97.4 $\pm$ 24.1
KF:KE	(N:N)	0.57 $\pm$ 0.11	0.55 $\pm$ 0.14	0.55 $\pm$ 0.16	0.54 $\pm$ 0.13	0.59 $\pm$ 0.13	0.58 $\pm$ 0.16

**Abbreviations:** SA, skeletal age; CA, chronological age; KF, knee flexors, KE, knee extensors; f, absolute frequencies.

The characteristics of isometric strength at 30° and 60° of knee flexion for late, on time and early maturers from 11 to 16 years of age are presented in Figure 5.1. Cross-sectional analysis showed that isometric strength differs ( $p < 0.05$ ) by skeletal maturity groups [Panel A (KEim30°): 12 years (early and on time maturers performed, on average, 8.0N (34.0%) and 5.5N (23.3%) more than late maturing players, respectively); 14-15 years (early maturers performed, on average, 20.7N (38.5%) more than late maturing players); 15 years (early maturers were, on average, 17.6N (26.4%) stronger than on time maturing players). Panel B: (KFim30°): 11 to 13 and 15 years (early maturers performed, on average, 16.7N (29.5%) more than late maturing players); 12-13 years (on time maturers were, on average, 7.8N (16.9%) stronger than late maturing players); 13 and 15 years (early maturers were, on average, 14.2N (18.7%) stronger than on time maturing players). Panel C (KEim60°): 11 to 15 years (early maturers performed, on average, 27.3N (29.4%) more than late maturing players); 12 to 15 years (on time maturers were, on average, 18.3N (19.6%) stronger than late maturing players); 15 years (early maturers were, on average, 25.7N (17.0%) stronger than on time maturing players). Panel D (KFim60°): 11 to 16 years (early maturers performed, on average, 19.4N (33.1%) more than late maturing players); 13 and 15 years (early maturers were, on average, 16.7N (23.7%) stronger than on time maturing players)].



**Figure 5.1. Measured isometric strength of knee extensors (Panel A: KE 30°; Panel C: KE 60°) and knee flexors (Panel B: KF 30°; Panel D: KF 60°), aligned by skeletal maturity status and chronological age group.**

<sup>a</sup> significant difference late vs. on time maturers ( $p < 0.05$ ). <sup>b</sup> significant difference late vs. early maturers. <sup>c</sup> significant difference on time vs. early maturers.

Table 5.3 summarize the results from multilevel models for KEim30°, KFim30°, KEim60° and KFim60°. The four multilevel models indicate that the influence of skeletal maturity status on isometric strength was not significant after controlling for CA and FFM. The best-fitting models were:  $KEim30^\circ = 5.759 \times CA + 1.163 \times FFM$ ;  $KFim30^\circ = -19.369 + 2.691 \times CA + 0.693 \times CA^2 + 2.108 \times FFM$ ;  $KEim60^\circ = 4.553 \times CA + 3.134 \times FFM$ ; and,  $KFim60^\circ = -19.669 + 1.544 \times CA + 2.033 \times FFM$ . These models suggested that an increment of 1kg in FFM predicted isometric strength as follows: 1.2N (KEim30°), 2.1N (KFim30°), 3.1N (KEim60°) and 2.0N (KFim60°).

The significant variances for KEim and KFim models at level 1 indicated that each individual player significantly improved in isometric strength of the knee extensors and flexors from the baseline to final occasions (estimate  $> 1.96 \times SE$ ;  $p < 0.05$ ). The between-individual variance matrix (level 2) indicated significant individual differences in growth curves for isometric strength, and this is clearly reflected in curve intercepts (constant/constant,  $p < 0.05$ ; KEim30°, KFim30°, KEim60° and KFim60°) and slopes (age/age,  $p < 0.05$ ; KEim30°, KFim30° and KFim60°). The positive covariance between intercepts and slopes (KEim30° = 28.985±6.406; KFim30° = 37.312±9.152; KEim60° = 54.562±14.574; KFim60° = 31.435±7.540) suggested that the rate of improvement in both KEim and KFim continued to increase towards late adolescence years, independently of the angular positions.

**Table 5.3. Multilevel regression models for isometric strength outputs of knee extensors and knee flexors.**

	Isometric (30°)		Isometric (60°)	
	Knee Extensors	Knee Flexors	Knee Extensors	Knee Flexors
Fixed effects	Estimates	Estimates	Estimates	Estimates
Constant	NS	- 19.369 ± 7.102	NS	- 19.669 ± 6.656
CA centered	5.759 ± 0.867	2.691 ± 1.088	4.553 ± 1.485	1.544 ± 0.483
CA centered <sup>2</sup>	NS	0.693 ± 0.313	NS	NS
Skeletal maturity status				
On time vs Late	NS	NS	NS	NS
Early vs Late	NS	NS	NS	NS
Stature	NS	NS	NS	NS
Fat-free mass	1.163 ± 0.131	2.108 ± 0.170	3.134 ± 0.251	2.033 ± 0.159
Random effects				
Level 1				
Constant ( $\epsilon_{ij}$ )	129.599 ± 13.444	126.46 ± 14.447	401.814 ± 41.510	98.913 ± 11.272
Level 2				
Constant ( $\mu_j$ )	42.799 ± 13.344	90.791 ± 21.149	141.062 ± 40.827	88.472 ± 19.139
CA centered ( $\nu_j x_{ij}$ )	11.356 ± 4.276	19.003 ± 6.394	NS	13.089 ± 4.722
$\mu_j \times \nu_j x_{ij}$	28.985 ± 6.406	37.312 ± 9.152	54.562 ± 14.574	31.435 ± 7.540

Fixed effect values are estimated mean coefficients ± standard error of estimate (SEE) of isometric (30° and 60°) strength in N. Random effect values are estimated mean variance ± SEE of isometric strength in N<sup>2</sup>.

CA centered is chronological age in years centered around 13.83 years of age (years). NS = Not significant and variable removed from the final model.

A visual inspection of Bland-Altman plots (not shown) was also performed to examine the agreement between predicted and actual KEim and KFim. This was performed using the random selection of about half of the original sample. The mean differences between actual and predicted values were ( $p > 0.05$ ):  $-0.1 \pm 5.7\text{N}$  (KEim $30^\circ$ ),  $-0.5 \pm 5.4\text{N}$  (KFim $30^\circ$ ),  $0.3 \pm 5.9\text{N}$  (KEim $60^\circ$ ), and  $-0.1 \pm 4.1\text{N}$  (KFim $60^\circ$ ). Intra-individual differences were normally distributed for the four models (heteroscedasticity diagnostic:  $r = 0.02$  to  $0.08$ ). Therefore, none of the statistical assumptions of the equations cross-validation were violated.

## **5.5. Discussion**

Muscle strength is a relevant fitness component (isometric, concentric and eccentric isokinetic, medicine ball throw, squat and counter-movement jump). Its different forms of expression depend from several muscular, neural and mechanical factors. The current study was aimed at examining longitudinal changes in isometric strength of the knee flexors and knee extensors at two different angular positions ( $30^\circ$  and  $60^\circ$ ) among male adolescent soccer players aged 11-16 years. It was possible to extract significant multilevel models for knee extensors and knee flexors (in two distinct angular positions). Data suggested that CA and longitudinal changes in FFM essentially explained isometric strength of the lower limbs. Although differences were apparent by skeletal maturity as presented in Figure 5.1, the indicators of biological maturation did not enter in the longitudinal models. This confirms that maturity-associated variation in functional capacities were more apparent in motor tasks that require body displacement (Figueiredo et al., 2009) and in the case of isometric strength outputs of the lower limbs age, and by inference, training experience, plus FFM probably mediate the potential effect of biological maturation.

The contribution of specific body size descriptors like FFM as longitudinal predictors were previously commented for explosive lower limb power from childhood to adulthood in high-performance soccer players (Deprez et al., 2015). The effect of FFM that correlates with “muscularity” of the players seemed significant in



jumping performance when players entered late adolescent years (16-20 years). During late childhood (7-10 years) and early adolescence (11-15 years), after controlling for chronological age and stature, fat mass was the main predictor of explosive leg power (inversely correlated). This is consistent with the findings of the current study.

Age-associated development in strength is attributable to changes in body size (De Ste Croix, 2007). Cross-sectional studies demonstrated the positive influence of CA on strength development (Sunnegardh, Bratteby, Nordesjo, & Nordgren, 1988; Kanehisa, Yata, Ikegawa, & Fukunaga, 1995) and longitudinal research added the influence of annual changes in stature and body mass (De Ste Croix et al., 2003). The patterns, sequences, and timing of physical changes during adolescence were described for 94 girls longitudinally assessed from childhood to mature state and it was concluded that developmental changes in isometric strength was uniquely apparent during late childhood and early pubertal years when expressed per unit of body mass (Faust, 1977). An increase in strength per body mass was noted from timing of peak height velocity through mature state (De Ste Croix, Deighan, Ratel, & Armstrong, 2009). Additionally, the peak in annual strength changes occurred slightly after peak height velocity and longitudinal studies confirmed stature and body mass as longitudinal predictors of muscle strength (Maffulli, King, & Helms, 1994; De Ste Croix et al., 2003; Malina et al., 2004b).

Age-specific mean values of the present sample for stature plotted on the 50% percentile of United States references (Center for Disease Control and Prevention) at ages 11-13 years. Afterwards, at ages 14-16 years mean values ranged between percentiles 75% and 95%. Mean body masses by age group fluctuated around 50% percentile for all ages, in contrast to previous studies that suggested a trend for larger body mass of late adolescent soccer players when compared to the general population (Malina et al., 2000). This was possibly due to absence of age-associated variation in the frequencies of players classified as advanced and as skeletally delayed. This trend was apparent after the age of 14 years (Malina et al., 2000) among elite Portuguese players, probably reflecting sport selection. The present

sample is composed of players of various competitive levels (local, sub-elite, elite) and the effect of maturation was not significant on intra-individual annual changes. The results of our study are consistent with previous study that did not evidence type of sport, puberty stage, and stature exerting a significant effect on maximum isometric voluntary contraction strength measured using a custom-made chair, but age did (Maffulli et al., 1994). The authors of the previously mentioned study stated that maximal isometric voluntary strength exerted by the quadriceps was proportional to body mass. Longitudinal observations of 20 schoolboys aged 10-14 years showed no influence of maturity status (given by stage of pubic hair) on both isokinetic knee extension and flexion strength (De Ste Croix et al., 2003). Similar observations were also noted in another study (Maffulli et al., 1994) reporting strength values of young athletes. Note, however, that biological maturation corresponds to inter-individual variation in body size descriptors such as stature, body mass and fat-free mass (Malina et al., 2004a; Figueiredo et al., 2009) and these sources of variability are interpreted as determinants of isometric strength. In the study of muscle strength expressed in N, comparisons between individuals are often controlled for body mass using traditional ratios  $N \cdot kg^{-1}$ . It is therefore recommended to use adequate techniques to obtain size-free strength outputs (De Ste Croix et al., 2009). The relationships between knee joint isokinetic strength, biological maturity status and body size were examined in 14-16-year-old basketball players, considering proportional allometric modeling (Carvalho et al., 2012) and proportional allometric models indicated that the influence of somatic maturation on isokinetic strength performance was mostly mediated by corresponding changes in overall body mass.

Among professional soccer players, balance between knee flexors and knee extensors were suggested to be crucial for injury prevention (Reilly & Thomas, 1977). Diagnosis of imbalances between KE and KF (in general and at specific angles) during pubertal years should be a focus of attention among athletic trainers and coaches in youth sports. The isometric strength assessment of KE and KF was examined in male soccer players classified by competitive level (national team; division I; division IV) in parallel to a group of non-soccer players and the ratio KF:KE was significantly higher for soccer players than for non-soccer players

(Oberge et al., 1986). Moreover, correction for inter-individual variation in body size did not change the conclusions presented above.

Fat-free mass was consistently a longitudinal predictor of isometric strength. At angular position of 30 degrees, KF increased from 43.7N to 104.5N from 11 to 16 years of age. The correspondent increment for the KE was 223%, that is 25.5 N (11 years) through 82.3N (16 years). Regarding the angular position of 60 degrees, increments were 133% for KE and 135% for KF. Not surprisingly,  $KF_{im30^{\circ}}:KE_{im30^{\circ}}$  decreased with age: 1.71 at 11 years to 1.27 at 16 years. Meantime,  $KF_{im60^{\circ}}:KE_{im60^{\circ}}$  remained stable across age, fluctuating between 0.54 and 0.59. This trend was consistent with the literature (Oberge et al., 1986). The developmental models and curves obtained in the present study can be used by trainers and coaches in order to predict the optimal developmental of  $KE_{im}$  and  $KF_{im}$  across pubertal years. The best-fitting equations are:  $KE_{im30^{\circ}} = 5.759 \times CA + 1.163 \times FFM$ ;  $KF_{im30^{\circ}} = -19.369 + 2.691 \times CA + 0.693 \times CA^2 + 2.108 \times FFM$ ;  $KE_{im60^{\circ}} = 4.553 \times CA + 3.134 \times FFM$ ;  $KF_{im60^{\circ}} = -19.669 + 1.544 \times CA + 2.033 \times FFM$ . These equations were satisfactorily cross-validated.

The present study has limitations that should be recognized. A previous study identified annual volume training as a significant predictor of soccer-specific skills and functional capacity from 11 to 17 years (Valente-dos-Santos et al., 2012). The current study did not obtain individual information about annual volume training. Future studies need to consider specific information about the intensity of training sessions. Additionally, future longitudinal research should obtain concentric and eccentric information about knee extension and flexion functions and examine the conventional and functional ratios at particular angles as a more informative alternative to ratios derived from peak torques of the Hamstrings and Quadriceps at different angles. Finally, Dual-energy X-ray Absorptiometry (DXA) may elucidates new hypothesis regarding the contribution of appendicular size descriptors (lower limb lean soft tissue) as an alternative to estimates of overall body size descriptors to explain inter-individual and intra-individual variability in strength protocols used to assess knee muscle actions in a seating position.

## **5.6. Conclusions**

The present study demonstrated that there is significant intra-individual and also inter-individual variation in lower-limb isometric strength performance in both knee extensors and knee flexors in adolescent soccer players. Multilevel models suggested that the influence of maturation on isometric strength performance overlapped with age-associated variation in FFM. The results of the current present study do not support the hypothesis of neuromuscular maturation independently from body size descriptors. For investigating longitudinal changes in strength outputs of the knee joint during adolescence the use of proportional multiplicative allometric models to normalize data for total and regional size descriptors is recommended.

## **5.7. Acknowledgements**

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## **Chapter VI**

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### **Study 4**

**Multilevel modelling of longitudinal changes in isokinetic knee extensors and flexors strength in adolescent soccer players**



## **6. Multilevel modelling of longitudinal changes in isokinetic knee extensors and flexors strength in adolescent soccer players**

*Reference: Duarte, J. P. et al. (2018). Multilevel Modelling of Longitudinal Changes in Isokinetic Knee Extensor and Flexor Strength in Adolescent Soccer Players. Ann Hum Biol. TAHB-2018-0057.R1*



## 6.1. ABSTRACT

The purpose of the study was to model the longitudinal development of knee extensors (KE) and flexors (KF) strength in adolescent soccer players. A mixed-longitudinal sample composed of 67 soccer players aged 11.0-13.9 years at baseline was followed on 3-5 occasions over five years. Stature, body mass and several skinfold thicknesses were measured. Fat mass was estimated from skinfolds and fat-free mass (FFM) derived. Skeletal age was estimated with TW2-RUS protocol. Isokinetic dynamometer was used to obtain peak torque of KE and KF from concentric assessments at an angular velocity of  $180^{\circ}\cdot\text{s}^{-1}$ . Multilevel random effects regression analyses were performed. Among youth soccer players aged 11-16 years, isokinetic strength of the knee muscle groups were reasonably predicted from chronological age (CA), stature and FFM:  $\text{KE} = -66.170 + 5.353 \times (\text{CA}) + 0.594 \times (\text{CA}^2) + 0.552 \times (\text{stature}) + 1.414 \times (\text{FFM})$ , and  $\text{KF} = -9.356 + 2.708 \times (\text{CA}) + 1.552 \times (\text{FFM})$ . In conclusion, CA per se accounted for annual increments of 5.4N m in KE and 2.7N m in KF.

**Keywords:** skeletal maturation; peak torque; developmental changes; youth soccer.



## **6.2. Introduction**

The development of the functional attributes during childhood and adolescence is reasonably documented for the general population (Malina et al., 2004). Among youth soccer players, multilevel longitudinal models have been used to explain developmental changes for repeated sprinting ability (Valente-dos-Santos et al., 2012), aerobic performance given by the Yo-Yo intermittent recovery test (Deprez et al., 2014), and explosive leg power (Deprez et al., 2015). Multilevel longitudinal models for the development of isokinetic strength in youth soccer players are lacking.

Strength reflects the ability to exert maximum muscular force statically or dynamically. Dynamic strength is seemingly more appropriate for soccer (Stolen et al., 2005). Concentric isokinetic strength of knee extensors (KE), for example, was included among determinants of a change-of-direction test in elite adult male soccer players (Chaouachi et al., 2012). Among British youth followed longitudinally from 10 to 14 years (De Ste Croix et al., 2002), multilevel regression modelling was used to evaluate the influence of age, sex, body size, adiposity and stage of puberty on the development of isokinetic knee extension and flexion. Age, sexual maturation and thigh muscle cross-sectional area failed to predict longitudinal changes in KE and knee flexor (KF) peak torques after body size was controlled. The limitation of stages of pubic hair for comparisons of boys and girls should be noted (Sherar et al., 2004).

Information on the longitudinal development of isokinetic strength during adolescence using skeletal age (SA), an established maturity indicator, is lacking. The present study was aimed to model the longitudinal development of isokinetic concentric muscular actions of the knee (extension and flexion) in adolescent soccer players using multilevel modelling. It was hypothesized that during years of maximum growth, which overlap with sport specialization in youth soccer, developmental changes of KE and KF are differently explained by chronological age (CA), skeletal maturity status, and body size.



## 6.3. Methods

### Procedures

The Ghent Youth Soccer Project (GYSP) was approved by the Ethics Committee of Ghent University Hospital. Details of the project have been previously reported; the data were collected between 1996 and 2000 (Philippaerts et al., 2006).

### Participants

Youth players were recruited from several clubs in the provinces East-Flanders and West-Flanders. The sample included 67 male players 11.0-13.9 years at baseline. They were followed for 5 years (290 observations).

### Age and skeletal maturity

SA was determined from hand-wrist radiographs using the TW2 RUS protocol (Tanner et al., 1983). The difference between CA and SA was used to classify maturity status of the player at each observation: average, SA within  $\pm 1.0$  year of CA; late, SA younger than CA by  $>1.0$  year; and early, SA older than CA by  $>1.0$  year (Malina et al., 2004). SA was not assigned if a player was skeletally mature.

### Anthropometry (including estimates of body composition)

Anthropometry included stature (Harpenden stadiometer 98.603, Crosswell, UK), body mass (SECA balance 770, MD, USA) and skinfold thicknesses (Lange Caliper, MI, USA) required to estimate fat mass using an established protocol for adolescent boys (Parizkova, 1977). Fat-free mass (FFM) was derived. All measurements were taken by a single trained observer adopting standardized procedures (Lohmann et al., 1988).

### Strength assessment

Participants performed a 5-min warm-up on a cycle ergometer (Monark 814E, Varberg, Sweden). Cadence was settled between 50 and 60 rpm adopting a standardized braking force (2% of body mass). The warm-up also included 20-s static stretching for the Quadriceps, Hamstrings and Adductors. A Biodex System 2 dynamometer (Shirley, USA) was used to assess isokinetic strength of the KE and KF of the preferred lower extremity at an angular velocity of  $180^{\circ}\cdot\text{s}^{-1}$ . Participants were seated as defined by the manufacture. Prior to each test, individual calibration was completed for gravity correction determined at the position of  $30^{\circ}$  of knee flexion. A 3-repetition trial was conducted prior to each isokinetic test to facilitate familiarization at  $180^{\circ}\cdot\text{s}^{-1}$ . A 60-s interval was settled between familiarization and the isokinetic test composed of five continuous maximal repetitions with real-time visual feedback. The highest peak torque was recorded and retained for analysis. Peak torques were individually used to determine the ratio (Oberg et al., 1986) = KF:KE.

### Statistical analysis

Descriptive statistics were calculated by age group (11-16 years). Multilevel modelling using hierarchical random effects models (Baxter-Jones et al., 1993), was used to predict developmental changes on isokinetic torque performances (MLwiN version 2.26 software, Centre for Multilevel Modelling; University of Bristol, UK). Two levels were considered (level 1: within-individual variation; level 2: between-individuals variation). A stepwise procedure was performed, i.e., fixed effects were added as significant if the estimated mean coefficient was greater than twice the standard error of estimate.

## 6.4. Results

Table 6.1 summarizes descriptive statistics. Stature, body mass and estimated FFM increased, on average, with CA. Given growth in FFM, changes in fat mass with age are relatively small. Estimated gains in isokinetic strength between 11 and 16 years are 78.3 N·m (168%) for KE and 48.3 N·m (146%) for KF.

**Table 6.1. Descriptive statistics (mean ± standard deviation or frequencies) for all measurements by age group (n=290).**

Variable (units)	11 years (n=29)	12 years (n=68)	13 years (n=65)	14 years (n=56)	15 years (n=45)	16 years (n=27)
CA (years)	11.44±0.39	12.52±0.30	13.43±0.30	14.45±0.27	15.53±0.29	16.52±0.36
SA (years)	11.94±1.11	12.71±1.45	13.70±1.14	14.68±1.11	15.99±1.08	16.98±1.08
SA/CA	1.04±0.09	1.02±0.11	1.02±0.09	1.02±0.08	1.03±0.07	1.03±0.07
SA-CA (years)	0.50±0.01	0.19±1.43	0.27±1.14	0.23±1.16	0.46±1.13	0.46±1.09
Stature (cm)	147.2±5.8	152.1±7.6	159.6±8.3	167.0±8.3	172.8±7.6	177.2±7.7
Body mass (kg)	37.1±6.3	40.6±0.4	46.9±8.8	52.8±10.4	59.2±8.9	62.8±8.1
Fat mass (%)	17.1±4.9	15.9±3.7	15.9±4.5	15.5±4.3	14.5±3.0	14.8±2.3
Fat mass (kg)	6.5±2.9	6.7±2.8	7.6±3.4	8.4±3.8	8.8±3.0	9.4±2.2
FFM	30.6±4.0	33.8±5.3	39.3±6.3	44.4±7.6	50.4±6.5	53.5±6.7
KE <sup>a</sup> (N m)	46.7±10.2	57.5±13.5	75.5±17.5	94.8±21.7	109.5±22.1	125.0±25.6
KF <sup>a</sup> (N m)	33.1±7.8	39.2±9.3	49.3±11.9	63.9±17.4	71.6±15.5	81.4±18.1
Ratio: KF:KE	0.67±0.08	0.69±0.11	0.66±0.10	0.68±0.13	0.66±0.09	0.67±0.18

**Abbreviations:** CA, Chronological age; SA, skeletal age; KE, knee extensors; KF, knee flexors;  
<sup>a</sup>Angular velocity: 180°·s<sup>-1</sup>.

Two significant multilevel models are summarized in Table 6.2. Significant longitudinal predictors of peak torque of KE are CA centered, CA centered<sup>2</sup>, stature and FFM. Significant longitudinal predictors of peak torque of KF are CA centered and FFM. The best-fitting models correspond to Equations (1) and (2). An increase of 1 year in CA corresponds to about 5.4N m in KE and 2.7N m in KF.

$$\text{KE} = -66.170 + 5.353 \times (\text{CA}) + 0.594 \times (\text{CA}^2) + 0.552 \times (\text{stature}) + 1.414 \times (\text{FFM}) \quad (1)$$

$$\text{KE} = -9.356 + 2.708 \times (\text{CA}) + 1.552 \times (\text{FFM}) \quad (2)$$

**Table 6.2. Multilevel regression models for isokinetic strength of knee extensors and knee flexors assessed at an angular velocity of  $180^{\circ}\cdot\text{s}^{-1}$ . Fixed effect values are Estimated Mean Coefficients  $\pm$  SEE of isokinetic ( $180^{\circ}\cdot\text{s}^{-1}$ ) strength (N·m), while random effect values are Estimated Mean Variance  $\pm$  SEE.**

Variables	Isokinetic ( $180^{\circ}\cdot\text{s}^{-1}$ )			
	Knee Extensors <sub>concentric</sub>		Knee flexors <sub>concentric</sub>	
Fixed effect	Estimates		Estimates	
Constant	$-66.170 \pm 23.492$		$-9.36 \pm 3.96$	
CA centered	$5.35 \pm 0.88$		$2.71 \pm 0.64$	
CA centered <sup>2</sup>	$0.59 \pm 0.25$		NS	
Skeletal maturity status				
On time vs. Late	NS		NS	
Early vs. Late	NS		NS	
Stature	$0.552 \pm 0.191$		NS	
Fat-free mass	$1.414 \pm 0.248$		$1.55 \pm 0.10$	
Fat mass	NS		NS	
Random effects	Level 1		Level 1	
Constant	$110.73 \pm 1.94$		$50.19 \pm 5.77$	
	Level 2		Level 2	
	Constant	CA centered	Constant	CA centered
Constant	$52.28 \pm 13.53$	$16.78 \pm 4.71$	$20.21 \pm 6.03$	$10.54 \pm 2.96$
CA centered	$16.78 \pm 4.71$	$2.71 \pm 2.98$	$10.54 \pm 2.96$	$8.07 \pm 2.57$

CA centered: centered on a chronological age (CA) of 13.83 years. Numerical values are all significant,  $p < 0.05$  (mean  $> 1.96 \cdot \text{SEE}$ ). NS: Not significant, and the variable was removed from the final model.

## 6.5. Discussion

Earlier studies (Maffulli et al., 1994; De Ste Croix et al., 2003) suggested that CA was the major factor influencing changes in isometric and isokinetic strength across adolescence, but the specific contributions of changes in body composition and biological maturation were not systematically addressed. The current study confirmed improvements in isokinetic strength associated with CA, but the multilevel model also indicated that stature and estimated FFM significantly contributed to estimated annual gains in isokinetic strength for KE and KF across adolescence in youth soccer players. CA was included in the predictors for both KE and KF, but had a smaller influence on KF compared to KE. Among youth soccer players, change in CA not only indicates the passage of time *per se*, but also includes potential effects of systematic training in the sport across time.

The lack of a significant effect of skeletal maturity status on the regression models was not entirely unexpected. Among 20 school boys followed from 10 to 14 years, stage of puberty did not explain developmental trajectories of isokinetic leg strength once body size was statistically controlled (De Ste Croix et al., 2002). In an independent sample of Flemish youth soccer players 11-14 years, developmental changes in the standing long jump were also independent of maturity status based on predicted age at peak height velocity (PHV) (Deprez et al., 2015). The latter results should be interpreted cautiously given limitations of the prediction equation. In two validation studies, predicted ages at PHV increased with CA at prediction, had reduced ranges of variation, and overestimated age at PHV in early maturing boys and underestimated age at PHV in late maturing boys (Malina & Koziel, 2014; Malina et al., 2016).

The relationship between muscular strength and FFM is reasonably well documented during late childhood through adolescence (Malina et al., 2004) and longitudinal observations indicated a significant influence of body size on explosive leg power from childhood into young adulthood among male Belgian soccer players (Deprez et al., 2015). On the other hand, the relationship between body size and isokinetic knee strength is less documented. Available information suggested that annual gains in overall body size accounted for 40% to 70% of the variance in strength during the years of the adolescent growth spurt (De Ste Croix et al., 2003). The remaining variance was likely related to variation in body composition. The current mixed-longitudinal study of youth soccer players noted that FFM influenced isokinetic strength for both KE and KF (Table 6.2). The results suggested that 1kg of estimated FFM represented an annual gain of 1.6 N·m in isokinetic KF strength and 1.4N·m in isokinetic KE strength. Dynamic muscular strength (concentric) is generally viewed as having an important role in activities characteristic of soccer and other sports - as in sprints, jumps, kicks and passes. Although coach interventions often involve efforts to manage body composition, emphasis is often on relative fatness.

The present study has several limitations. Isokinetic strength was measured at a specific angular velocity ( $180^{\circ}\cdot\text{s}^{-1}$ ). Although slow angular velocities are recommended to examine strength deficiencies of the knee extension and knee flexion, fast angular velocities are viewed as more informative in the context of sport (Undheim et al., 2015). The derived multilevel models are unique for youth soccer players aged 11-16 years. Additionally, it has been recommended modified isokinetic dynamometer protocols for youth in order to isolate muscle group actions (e.g., to place a back pad behind the observed children to allow the lower limbs to hang freely from the edge of the seat). The present study did not consider any adjustment. Finally, the current study derived the conventional ratio from peak torques of concentric mode assessments of the knee extension and knee flexion obtained at different angles. Future studies should consider agonist and antagonist relationships at specific angles. The literature claims for functional ratios (functional extension ratio and functional flexion ratio) that require assessments including eccentric mode of the knee action in the protocol. Unfortunately, information about data quality in the present study was not available across time. Although reliability of adopted protocols has been reported in children with intra-individual correlation about 0.85-0.95 (Deighan et al., 2003), the literature (De Ste Croix et al., 2003) recommended a session for habituation. Although estimates of body composition based skinfold thickness have limitation, they are accepted as a valid non-invasive alternative authorized by ethics committees. A variety of models and methods have been used to partition body mass into fat and lean components and, as technologies have become refined, models have evolved from the traditional two compartments (as in the present study) to models comprising several compartments depending on level of analysis (whole body, tissue, molecular, atomic). Future studies of isokinetic strength should perhaps include a measure of lower limb mass obtained from Dual-energy X-ray Absorptiometry.

The literature on developmental models for predicting intra- and inter-individual variability on isokinetic knee extension and flexion strength is limited. The current study noted distinct models for each muscle group. The multilevel model for KE was a polynomial based on CA, body size and FFM, while the model for KF

was based on a linear combination of CA and estimated FFM. The power function for age may be a consequence of the overlap between age *per se* and years of training. As such, the models may facilitate the understanding of potential muscle imbalances and assist in the training process.

## 6.6. Acknowledgments

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## **Chapter VII**

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### **Study 5**

#### **Longitudinal changes in functional isokinetic leg strength in youth soccer players**



## **7. Longitudinal changes in functional isokinetic leg strength in youth soccer players**



## 7.1. Abstract

This study used multilevel regression modeling to longitudinally examine the influences of age, biological maturation, training, and body size and composition on the development of isokinetic knee extension and flexion on four-time moments over a 2-year period. A mixed-longitudinal sample of thirty male soccer players was measured and 108 isokinetic leg strength tests and associated measures were successfully concluded. Subjects were aged  $12.2 \pm 0.6$  years at the baseline of the study. Stature, body mass, estimated leg length, and isokinetic strength (peak torque of KE and KF from concentric and eccentric assessments at an angular velocity of  $60^{\circ}\cdot s^{-1}$ ) were measured. Fat mass, FFM, and lower limb preferred LST were assessed by DXA. Skeletal age was assessed according to the Fels method. Multilevel random effects regression analyses extracted developmental polynomial models. An annual increment of 1 year in CA predicted  $-1.5\%$  on KFecc:KEcc and  $4.7\%$  on KFcc:KEecc. For KFecc:KEcc an increment of 1cm on ELL predicted  $-1.4\%$ , while a 1kg on DXA preferred thigh LST estimates  $+3.0\%$ . The following equations were obtained:  $KFecc:KEcc = 1.689 - 0.015 \times CA - 0.014 \times ELL - 0.030 \times DXA$  preferred thigh LST; and,  $KFcc:KEecc = 0.616 + 0.047 \times CA$ . Monitoring increases in anthropometrical characteristics (i.e., estimated leg length and FFM) allow youth soccer coaches to better understand the players' individual development of knee joint imbalances. The use of the functional knee joint isokinetic ratios is recommended because the biological maturity status has effect in KF:KE imbalances development through puberty.

**Keywords:** muscle strength; knee joint stability; ecc:con; con:ecc.



## **7.2. Introduction**

Tackling, kicking, jumping, sprinting, dribbling, and changing of direction are intense and explosive movements that characterized intermittent actions required by soccer (Stolen, Chamari, Castagna, & Wisloff, 2005). Previous literature has indicated a strong correlation between maximal strength, sprinting and jumping performance in elite soccer players (Wisloff, Castagna, Helgerud, Jones, & Hoff, 2004). The relative match-play demands are consistent across the ages of under13-15 (Harley et al., 2010), and apparently strength seems to be essential in match demands of youth soccer players (Lehance, Binet, Bury, & Croisier, 2009).

Maximal strength can be defined as the result of force-producing muscles performing maximally, either an isometric or dynamic pattern during a single voluntary effort of a defined task (Hoff & Helgerud, 2004). Knee muscles strength is commonly measured as the maximal force generated or moments of force produced (in N and N m, respectively) under standardized conditions (Sale, 1991). Eccentric (ecc) muscular actions are likely to occur in everyday life as often as concentric (cc) actions. Regarding knee joint, these actions play a significant role in knee extensors (KE) in shock absorption during walking, running and jumping and in the knee flexors (KF) play the role of braking as the knee extends during walking, kicking and running (De Ste Croix, Deighan, & Armstrong, 2003). In soccer specific patterns, the quadriceps muscles are concentrically requested in passes, kicks, and jumps (Ruas, Minozzo, Pinto, Brown, & Pinto, 2015). Contrariwise, the Hamstrings are eccentrically used to control, decelerate and stabilize the knee, but are also used concentrically to sprint, turn and tackle (Ruas et al., 2015).

Ecc:cc reflects the magnitude of the torque differences between the muscle action portions of the torque-velocity curve (De Ste Croix et al., 2003). This functional strength ratio between may result from soccer specific skills. There are few available studies measuring the functional ratio in male young soccer players. Cross-sectional data have found significantly higher ecc strength compared with cc strength (Kellis, Kellis, Gerodimos, & Manou, 1999; De Ste Croix et al., 2003;



Lehance et al., 2009). Kellis et al. (1999) assessed 30 young Greek amateur soccer players ( $13.0 \pm 0.4$ ) and found significant mean differences between KFcc moments and KEecc moments. The same trend of results was found in under-17 Belgian players ( $15.7 \pm 0.8$ ), who counted significantly knee joint muscular asymmetries (Lehance et al., 2009).

Muscular strength is the basis of most soccer movements, and many of which are executed from a single leg (Bressel, Yonker, Kras, & Heath, 2007). Soccer tasks may also modify lower-extremity strength, joint imbalances and asymmetry, which may also be position specific (Ruas et al., 2015). Very few studies have used isokinetic dynamometers to determine the development of functional muscle strength in young soccer players (Duarte et al., 2018). There is a lack of studies examining the effect of stage of maturation on functional isokinetic strength. Considering previous research on isokinetic longitudinal developmental changes, it was hypothesized that biological maturation and muscularity are relevant longitudinal predictors of functional muscle strength.

### **7.3. Methods**

#### Procedures

The research leader of the Coimbra Youth Soccer Longitudinal Project contacted clubs from the Centre Region of Portugal. Clubs represented regional competition level. The study adopted a mixed-longitudinal design. The cohorts ranged between 11.0 and 13.0 years of age at baseline. Measurements were performed over two years. Therefore, it was possible to estimate a consecutive developmental trend (12.5-14.0 years). The study was conducted in accordance with established ethical procedures for Sports Medicine (Harriss, Macsween, & Atkinson, 2017) and approved by Ethics Committee of Faculty of Sports Science and Physical Education of the University of Coimbra (CE/FCDEF-UC/00182016). Adolescent players were instructed not to eat and drink coffee or substances containing caffeine at least 3

hours before testing sessions. Assessments were performed during school holidays (December and June) during the same day period time (9.00-12.30 a.m.). All tests were completed within a single week. An initial testing session was used for anthropometry and isokinetic assessment and a second session to visit the hospital for the X-ray and Dual-energy X-ray Absorptiometry (DXA) exams needed for the determination of skeletal age (SA) and body composition, respectively.

#### *Participants and training experience*

Nineteen soccer players aged  $12.2 \pm 0.6$  years at baseline joined in this study. Players participated in a 9-month competitive season (September - May) through the Soccer Association. Coaches completed registration sheets with training experience (sessions and minutes) and competitive formal information (games and minutes). Informed written consent was individually obtained from parents or legal guardians. Participants were informed that participation was voluntary and that they could withdraw from the study at any time.

#### *Age and skeletal maturity*

Chronological age (CA) was calculated as the difference between the birth date and the date on which a radiograph of the left hand-wrist was taken. SA was assessed according to the Fels method (Roche, Chumlea, & Thissen, 1988). A single and trained observer assessed the radiographs. The method utilizes specific criteria for each bone of the hand-wrist and ratios of linear measurements of epiphyseal and metaphyseal widths. Ratings were entered into a computer program (Felshw 1.0 Software, Lifespan Health Research Center, Dayton, Ohio) that yields an SA and standard error of the estimate. The difference between SA and CA (SA minus CA) was used to classify players into maturity categories: late (delayed), SA younger than CA by  $> 1.0$  year; average (on time),  $SA \pm 1.0$  year CA; early (advanced), SA older than CA by  $> 1.0$  year; an SA was not assigned if the individual had attained skeletal

maturity. The band of 1.0 year is consistent with age-specific standard deviations for SAs in adolescent boys and allows for errors associated with assessments (Malina et al., 2010).

### Anthropometry

Stature, body mass and sitting height were measured by a single trained observer following standardized procedures (Lohman, Roche, & Martorell, 1988). Leg length was estimated as stature minus sitting height. Sitting height/stature ratio was calculated (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002). Intra-observer technical errors of measurement for anthropometric measures were as follows: stature, 0.3cm; sitting height, 0.3cm; body mass, 0.2kg.

### Dual-energy X-ray Absorptiometry (DXA)

Absorptiometry (fan-beam Lunar DPX-PRO) was used to measure whole body fat tissue (kg and %), and lean soft tissue (LST) (kg and %) using standard or thick mode depending on body stature. The machine's calibration was checked and passed on a daily basis using the Lunar calibration epoxy resin phantom. Participants were placed in the supine position on the scanning table with the body aligned along the central horizontal axis. Arms were positioned parallel to, but not touching the body. Forearms were pronated with hands flat on the bed. Legs were fully extended, and feet were secured with a canvas and Velcro support to avoid foot movement during the scan acquisition. One region of interest was manually positioned according to International Society for Clinical Densitometry guidelines and was apportioned as DXA preferred thigh LST. One skilled technician performed and analyzed all scans following the manufacturer's guidelines (Lunar Encore software, version 13.6).

### Strength assessment

A calibrated Biodex System 3 dynamometer (Shirley, USA) was used to assess isokinetic cc and ecc strength of the KE and KF of the preferred lower-limb at an angular velocity of  $60^{\circ}\cdot\text{s}^{-1}$ . At all testing sessions, participants performed a standardized 5-min warm-up on a cycle ergometer (Monark 814E, Varberg, Sweden). Cadence was settled between 50 and 60 rpm adopting a standardized braking force (2% of body mass). The warm-up also included 20-s static stretching for the Quadriceps, Hamstrings and, Adductors. Participants were placed in a seated position, as defined by the manufacturer, and the axis of rotation of the dynamometer lever arm was aligned with the lateral epicondyle of the knee. Prior to each test, individual calibration was completed for gravity correction determined at the position of  $30^{\circ}$  of knee flexion. To ensure full extension, anatomical  $0^{\circ}$  was determined as maximal voluntary knee extension for each subject. The range of motion for the knee test was  $5\text{-}90^{\circ}$  due to the need for an applied preload force of 10% of the ecc torque limits. For cc actions, participants were instructed to push the lever up, and pull it down, as hard and as fast as possible with extension undertaken first. For ecc actions, subjects were instructed to resist the lever arm with extension as the first movement. Familiarization included a 3-repetition trial conducted prior to each isokinetic test. A 60-s interval was settled between familiarization and the isokinetic test composed of five continuous maximal repetitions with real-time visual feedback. The highest peak torque was recorded and explored with *Acqknowledge* software version 4.1 (Biopac Systems, Goleta, USA). Peak torques were individually used to determine two functional ratios (Aagaard, Simonsen, Magnusson, Larsson, & Dyhre-Poulsen, 1998):  $\text{KF}_{\text{ecc}}:\text{KE}_{\text{ecc}}$  (extension) and  $\text{KF}_{\text{cc}}:\text{KE}_{\text{ecc}}$  (flexion).

### Statistical analysis

Means and standard deviations were determined for the total sample by time moment (1-4). All cross-sectional analyses were assessed using SPSS 24 for MAC OS X (Statistical Package for Social Sciences, SPSS, Chicago, USA). For the longitudinal

analyses, multilevel (hierarchical) random effects models were constructed using a multilevel modeling approach: MLwiN version 2.26 software, Centre for Multilevel Modelling; University of Bristol, UK (Goldstein, Browne, & Rasbash, 2002). A detailed description of the multilevel modeling procedures was described in previous work (Baxter-Jones, & Mirwald, 2004). In brief, strength functional extension ratio (KFecc:KEcc) and strength functional flexion ratio (KFcc:KEecc) were measured repeatedly in individuals (level 1 of the hierarchy) and between individuals (level 2 of the hierarchy). Analysis models that contain variables measured at different levels of a hierarchy are known as multilevel regression models. Specifically, the following additive random effects multilevel regression models were adopted to describe the developmental changes in strength ratios with age.

$$y_{ij} = (\alpha + \mu_j) + (\beta + \nu_j)\chi_{ij} + (z_{1ij} + z_{2ij} + \dots + z_{nij}) + \varepsilon_{ij} \quad (1)$$

CA ( $x$ ) was included in both the fixed and random parts of the model, which is apparent when equation 1 is reorganized into fixed and random components:

$$y_{ij} = (\alpha + \beta_j\chi_{ij}) + (z_{1ij} + z_{2ij} + \dots + z_{nij}) + (\mu_j + \nu_j\chi_{ij} + \varepsilon_{ij}) \quad (2)$$

where  $y$  was the KFecc:KEcc or KFcc:KEecc on measurement occasion  $i$  in the  $j$ th individual,  $\alpha$  was the constant for each  $j$ th individual,  $\beta_j\chi_{ij}$  was the slope for the ratios over time (in this model, age is centered around 13.11, the average age of the sample) for the  $j$ th individual; and  $z_1$  to  $z_n$  are the coefficients of explanatory variables (i.e., CA, stature, DXA whole body LST) at assessment occasion  $i$  in the  $j$ th individual. These are the fixed parameters in the model.

$\mu_j$ ,  $\nu_j\chi_{ij}$  and  $\varepsilon_{ij}$  are random quantities, whose means are equal to zero; they form the random parameters in the model. They are assumed to be uncorrelated and follow normal distribution assumptions, and thus, their variances can be estimated;  $\varepsilon_{ij} \sim \mathcal{N}[0, \text{var}(\varepsilon_{ij})]$  is the level-1 residual (within-individual) variance for the  $i$ th assessment of the strength functional ratios KFecc:KEcc or KFcc:KEecc in the  $j$ th individual.  $\mu_j \sim \mathcal{N}[0, \text{var}(\mu)]$  is the between-individuals intercept variance and

$v_{ij}x_{ij} \sim N[0, \text{var}(v_{ij}x_{ij})]$  is the between-individuals slope variance; these are interpreted as level-2 residual (between subjects) variances for the  $j$ th individual. The equation  $\mu_j \times v_{ij}x_{ij} \sim N[0, \text{var}(\mu_j \times v_{ij}x_{ij})]$  explained the intercept-slope covariance relationships among the intercepts and slopes in the model. A stepwise procedure was adopted, i.e. predictor variables ( $z$  fixed effects) were added one at a time, and likelihood ratio statistics were used to judge the statistical fit of the model. Predictors ( $z$ ) were accepted as significant if the estimated mean coefficient was greater than twice the standard error of the estimate; if the criterion was not attained, the predictor was discarded. CA power functions (centered  $CA^2$ ) were introduced into the linear models to allow for the nonlinearity of KFecc:KEcc and KFcc:KEecc ratios development. Based on analytical [i.e. Pearson's product moment correlations ( $r_{y,x}$ ) between performance parameters ( $y$ ) and potential predictors ( $x$ ) at baseline and measurement occasions 2, 3, 4] and biological assumptions, the following variables were considered in the multilevel models: centered CA, centered  $CA^2$ , skeletal maturity status (on time vs. late and early vs. late), body mass, stature, sitting height/stature ratio, estimated leg length (ELL), DXA whole body fat tissue, DXA whole body LST and DXA preferred thigh LST. A tolerance  $> 0.10$  and a variance inflation factor  $< 10$  were set to avoid collinearity between explanatory variables (Slinker, & Glantz, 1985). Comparisons of the multilevel model structures (KFecc:KEcc and KFcc:KEecc) were based on the Akaike information criterion (Akaike, 1974):  $-2 \log \text{likelihood} + 2 \text{ number of parameter fitted}$ . Heteroscedasticity was examined by calculating the correlation coefficients between the absolute differences corresponding mean (Nevill, & Atkinson, 1997) using GraphPad Prism version 5.03 software (GraphPad Software, La Jolla, USA). Alpha level was set at 0.05.

## 7.4. Results

Participants characteristics at all test occasions are summarized in Table 7.1. As anticipated, stature and body mass increased with CA. On average, fat tissue (kg)

increased, while the % fat fluctuated between 14.9% and 16.6%. At time-moment 1 all boys were classified accordingly skeletal maturity status. 21% were classified as “late”, 47% as “on time” and 32% as “early” mature. The percentages remained constant remained constant during the study. Other than KFecc all strength parameters improved with time. Regarding ratios analyses, for functional extension ratio mean values decreased from 0.98 to 0.74. The opposite occurred with the functional flexion ratio that increased from 0.40 to 0.50.

**Table 7.1. Descriptive characteristics (mean, standard deviation, frequencies) of the participants according to measurement occasion.**

Year Measurement occasion	1				2			
	1 (n=19)		2 (n=30)		3 (n=30)		4 (n=29)	
	Mean ± SD	F (%)	Mean ± SD	F (%)	Mean ± SD	F (%)	Mean ± SD	F (%)
CA (years)	12.22 ± 0.63		12.75 ± 0.75		13.33 ± 0.80		13.82 ± 0.82	
SA (years)	12.49 ± 1.33		13.10 ± 1.71		13.95 ± 1.62		14.63 ± 1.51	
SA/CA (years/years)	1.02 ± 0.09		1.03 ± 0.10		1.04 ± 0.08		1.06 ± 0.08	
SA-CA (years)	0.26 ± 1.10		0.36 ± 1.25		0.62 ± 1.09		0.81 ± 1.05	
Skeletal maturity status								
Late		4 (21.0)		7 (23.3)		7 (23.3)		7 (24.2)
On time		9 (47.4)		12 (40.0)		12 (40.0)		11 (37.9)
Early		6 (31.6)		11 (36.7)		11 (36.7)		11 (37.9)
Training experience (years)	5.63 ± 1.26		5.72 ± 1.60		6.33 ± 1.62		6.79 ± 1.65	
Training experience (sessions)	42 ± 10		31 ± 18		53 ± 15		43 ± 19	
Training experience (minutes)	3398 ± 1015		2738 ± 1868		4510 ± 1353		3744 ± 1735	
Competitive playing (games)	14 ± 5		11 ± 6		17 ± 5		14 ± 6	
Competitive playing (minutes)	786 ± 381		626 ± 433		1010 ± 441		859 ± 471	
Body mass (kg)	40.2 ± 5.9		44.0 ± 8.7		47.1 ± 8.9		50.2 ± 9.7	
Stature (cm)	149.5 ± 6.4		154.1 ± 6.9		158.3 ± 7.4		161.4 ± 7.4	
Sitting height (cm)	77.2 ± 3.5		80.0 ± 3.6		82.2 ± 4.2		83.8 ± 4.5	
Estimated leg length (cm)	72.3 ± 3.5		74.1 ± 4.5		76.0 ± 3.9		77.6 ± 3.7	
Sitting height/stature ratio (%)	0.52 ± 0.01		0.52 ± 0.01		0.52 ± 0.01		0.52 ± 0.01	
DXA whole body fat tissue (kg)	6.4 ± 4.0		7.7 ± 4.9		7.5 ± 4.6		7.8 ± 4.7	
DXA whole body fat tissue (%)	14.9 ± 7.9		16.6 ± 8.3		15.3 ± 7.4		15.0 ± 7.4	
DXA whole body lean soft tissue (kg)	30.5 ± 4.4		33.4 ± 5.8		36.8 ± 6.7		39.5 ± 7.6	
DXA whole body lean soft tissue (%)	80.2 ± 7.7		78.5 ± 8.2		79.9 ± 7.3		80.3 ± 7.2	
DXA preferred thigh lean soft tissue (kg)	2.5 ± 0.5		2.8 ± 0.6		3.1 ± 0.6		3.3 ± 0.7	
KEcc (N m)	92.0 ± 22.7		93.2 ± 24.7		111.4 ± 26.1		114.3 ± 31.4	
KFcc (N m)	50.7 ± 15.4		52.6 ± 14.9		64.6 ± 18.4		68.1 ± 20.0	
KEecc (N m)	131.3 ± 39.0		125.8 ± 35.2		140.1 ± 52.5		149.5 ± 66.0	
KFecc (N m)	87.7 ± 23.4		85.7 ± 30.6		87.2 ± 25.4		84.1 ± 28.1	
Functional extension ratio: KFecc:KEcc	0.98 ± 0.25		0.94 ± 0.30		0.79 ± 0.18		0.74 ± 0.16	
Functional flexion ratio: KFcc:KEecc	0.40 ± 0.10		0.43 ± 0.11		0.49 ± 0.12		0.50 ± 0.15	

**Abbreviations:** CA, Chronological age; SA, Skeletal age; DXA, Dual-energy X-ray Absorptiometry; KE, Knee extensors; KF, Knee flexors; cc, concentric; ecc, eccentric.



Table 7.2 presents the results from multilevel models for KFecc:KEcc and KFcc:KEecc. The two multilevel models indicate that the influence of skeletal maturity status on functional strength ratio was significant after controlling for CA. The best-fitting models, for late matures, were: KFecc:KEcc =  $1.689 - 0.015 \times CA - 0.014 \times ELL - 0.030 \times DXA$  preferred thigh LST; and, KFcc:KEecc =  $0.616 + 0.047 \times CA$ . For on time matures the models were the same as for late matures +0.303 and -0.016, respectively. For early matures +0.347 and -0.184, correspondingly. These models suggested that an increment of 1 year in CA predicted -1.5% on KFecc:KEcc and 4.7% on KFcc:KEecc. For KFecc:KEcc an increment of 1cm on ELL predicted -1.4%, while a 1kg on DXA preferred thigh LST estimates +3.0%.

**Table 7.2. Multilevel regression analysis of the functional knee strength ratios development in adolescent soccer players.**

Functional strength ratios				
Variables	Model 1: KF <sub>ecc</sub> :KE <sub>ecc</sub>		Variables	Model 2: KF <sub>cc</sub> :KE <sub>ecc</sub>
Fixed effect	Estimates		Fixed effect	Estimates
Constant	1.689 (0.599)		Constant	0.616 (0.064)
CA centered	-0.015 (0.004)		CA centered	0.047 (0.014)
Skeletal maturity status			Skeletal maturity status	
On time vs. late	0.303 (0.136)		On time vs. late	-0.132 (0.062)
Early vs. late	0.347 (0.137)		Early vs. late	-0.184 (0.069)
ELL	-0.014 (0.006)			
DXA preferred thigh LST	-0.030 (0.013)			
Random effects	Level 1		Random effects	Level 1
Constant	0.032 (0.006)		Constant	0.006 ± 0.001
	Level 2			Level 2
	Constant	CA centered	Constant	CA centered
Constant	0.016 (0.007)		0.008 (0.003)	
CA centered	-0.009 (0.004)	0.005 (0.005)	0.003 (0.001)	0.002 (0.001)

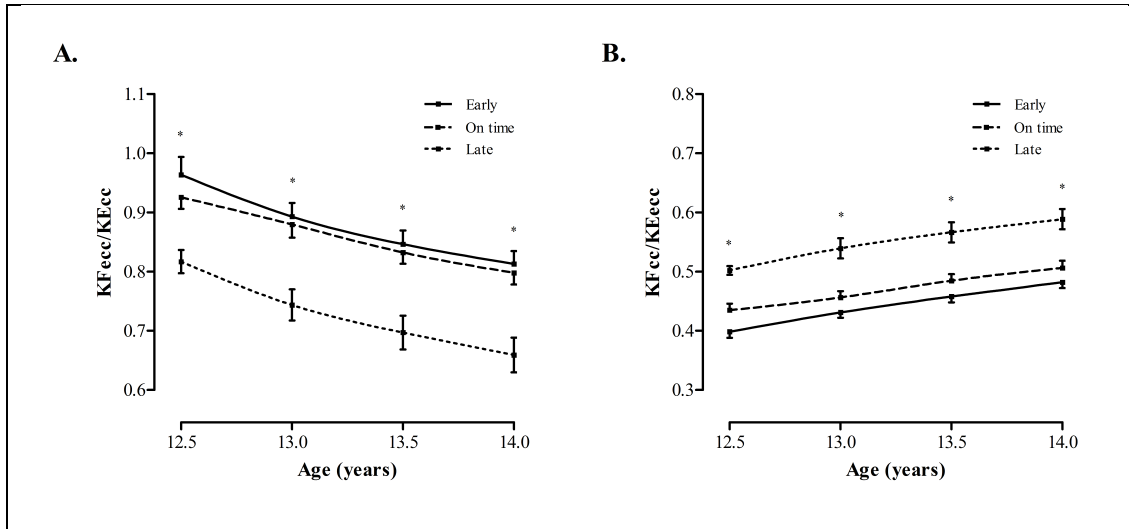
**Abbreviations:** CA, chronological age; ELL, estimated leg length; DXA, Dual-energy X-ray Absorptiometry; LST, lean soft tissue; KF Knee flexors; KE knee extensors; cc, concentric; ecc, eccentric.

Late maturers were used as a reference category and other skeletal maturity status groups were compared with it.

Fixed-effect values are estimated mean coefficients (standard error of estimate) of functional strength ratios. Random-effects values are estimated mean variance (SEE) in functional strength ratios<sup>2</sup>. Chronological ages were adjusted about origin using mean chronological age of 13.11 years. Non-significant variables were removed from the final model.

The significant variance at level 1 indicates that functional extension ratio improved significantly at each measurement occasion within individuals (estimate  $> 1.96 \times SE$ ;  $P < 0.05$ ), and functional flexion ratio decreased significantly at each measurement occasion within individuals (estimate  $> 1.96 \times SE$ ;  $P < 0.05$ ). The between-individual variance matrix (level 2) indicated significant individual differences in growth curves for KF:KE strength ratios, and this is clearly reflected in curve intercepts (constant/constant,  $p < 0.05$ ; KFecc:KEcc and KFcc:KEecc) and slopes (age/age,  $p < 0.05$ ; KFecc:KEcc and KFcc:KEecc). The negative and significant covariance between intercepts and slopes (SA/constant) of functional knee extension ratio suggests that rate of improvement on KFecc:KEcc decreases in late adolescence. The positive covariance between intercepts and slopes on functional knee flexion ratio suggested that the rate of improvement on KFcc:KEecc continued to increase towards late adolescence years.

The characteristics of knee joint functional ratios for late, on time and early maturers are presented in Figure 7.1. Cross-sectional analysis showed that functional knee ratios differed ( $p < 0.05$ ) by skeletal maturity groups [Panel A (KFecc:KEcc): 12.5 years (early and on time maturers performed, on average, +14% and +11% than late maturing players, respectively); 13.0 years (early and on time maturers performed, on average, +15% and +14% than late maturing players, correspondingly); 13.5 years (early and on time maturers performed, on average, +15% and +13% than late maturing players, respectively); and 14.0 years (early and on time maturers performed, on average, +15% and +14% than late maturing players, correspondingly). Panel B: (KFcc:KEecc): 12.5 years (early and on time maturers performed, on average, -3% and -7% than late maturing players, respectively); 13.0 years (early and on time maturers performed, on average, -3% and -9% than late maturing players, correspondingly); 13.5 years (early and on time maturers performed, on average, -2% and -9% than late maturing players, respectively); and 14.0 years (early and on time maturers performed, on average, -3% and -8% than late maturing players, correspondingly).



**Figure 7.1.** Mean predicted values ( $\pm$  SEM) for KFecc:KEecc (Panel A) and for KFcc:KEecc (Panel B), plotted by chronological age group.

\* significant difference late vs. on time maturers and late vs. early ( $p < 0.05$ ).

## 7.5. Discussion

In the present study, the two functional KF:KE strength ratios were calculated by expressing KFecc muscle strength relative to KEecc muscle strength (KFecc:KEecc) and KFcc muscle strength relative to KEecc muscle strength (KFcc:KEecc). To our knowledge, this study appears to be the first longitudinal study to have examined the development of isokinetic knee extension and flexion in both cc and ecc muscular actions, during growth and maturation, with soccer players. The multilevel model indicated that maturity status, ELL, and DXA preferred thigh LST significantly contributed to estimated isokinetic ratios across adolescence in youth soccer players. The use of the functional knee joint isokinetic ratios is recommended in youth soccer identification and selection programs because biological maturity status has effect in KF:KE imbalances development through puberty.

As hypothesized skeletal maturity status has a significant effect on the regression models. Therefore, an estimate of maturity status was considered as a model variable (later vs on time vs earlier maturing players based on SA-CA) and as a candidate variable in the analyses. Notably, compared to the latest maturing players, the on time and earliest maturing players presented significantly higher

KFecc:KEecc (+0.30 and +0.35, respectively; Table 7.2). For KFcc:KEecc model the latest maturing players, the on time and earliest maturing players presented lower ratios (-0.13 and -0.18, respectively; Table 7.2). Note that values of 1.00 for isokinetic open chain knee extension have been previously reported (Aagaard et al., 1998), and indicate a significant capacity of the KF to provide dynamic joint stabilization during active KE, and lower values of 0.30 have been reported for functional KFcc:KEecc ratios representative of isokinetic open-chain knee flexion.

In a group of under-17 players reported a significant age effect on strength performance in addition to that which could be accounted for by the increase in stature and body mass (Nevill, Holder, Baxter-Jones, Round, & Jones, 1998). According to the same group of authors, the age term identified could be explained by increasing levels of testosterone in boys (Round, Jones, Honour, & Nevill, 1999), which the authors linked to both maturation and the development of muscle mass. Ramos, Frontera, Llopart, and Feliciano (1998) suggested that increases in both muscle mass and neural maturation, which occur in conjunction with progression through puberty, may play a key role in the development of isokinetic leg strength.

Previous longitudinal observations indicated the relationship between isokinetic knee strength and estimation of FFM as being significant (De Ste Croix, Armstrong, Welsman, & Sharpe, 2002). Data from track and field athletes have indicated increases in isokinetic strength with age once changes in FFM have been accounted for (De Ste Croix et al., 2002; 2003). In the current study, the introduction of DXA preferred thigh LST was found to be a significant explanatory variable only in the development of KFecc:KEecc. This finding reinforces the importance of assessing isokinetic strength in different muscle actions and functions, as the factors associated with the development of strength with age may not be consistent across muscle function.

Contrarily to body composition, the relationship between body size and isokinetic knee strength is controversial. Some authors reported that stature may not play a major role in the development of muscle strength (Valente-dos-Santos et al.,

2014; Deprez et al., 2015), others demonstrated that increases in strength performance in under-17 soccer players could be partly explained by the increase in stature independent of body mass (Nevill et al., 1998). Data from our study support previous works findings as both stature and body mass did not influence functional knee extension and flexion movements. In accordance with the cited study of Deprez et al. (2015), the present findings revealed that, on average, an increase of 1cm in ELL would decrease  $K_{Fecc}:K_{Ecc}$  by 0.01.

The increase in ELL introduces a mechanical advantage, which occurs in conjunction with growth (De Ste Croix et al., 2002). The increase in the length of long bones (i.e. femur) leads to a stretch of the limb muscles, providing a stimulus for muscle development. Thus, Hamstrings flexibility is influenced by femur growth: better the hamstring flexibility, the longer the hamstring muscle optimal length (Wan, Qu, Garrett, Liu, & Yu, 2017). This is extremely important for isokinetic muscle assessment which is dependent of the arm length moment as an increase in limb length will provide a mechanical advantage due not only to the joint structure but also to the angle of muscle pennation (De Ste Croix et al., 2002).

## **7.6. Conclusions**

In summary, our findings are in accordance with previous literature suggesting that the development in strength is due to increases in muscle size rather than gains in stature and body mass. The current study demonstrated that DXA preferred thigh LST were related to isokinetic leg strength in the prediction of isokinetic  $K_{Fecc}:K_{Ecc}$ . The low values for  $K_{Fcc}:K_{Eecc}$  (0.40 - 0.50) are also consistent with previous literature and suggest that either the Hamstring muscles have reduced capacity for knee joint stabilization during dynamic knee flexion movements or that the Quadriceps have a high ecc capacity during knee flexion. The current study reinforces the importance of examining the knee joint functional ratios. Monitoring increases in anthropometrical characteristics (i.e., estimated leg length and FFM) on

a regular basis would allow youth soccer coaches to better understand the players' individual development of knee joint imbalances.

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## Section III KEY POINTS

Chronological age (CA) was a significant explanatory variable once body size, body composition, and maturation were taken into account;

Stature might not play a major role in the development of isometric strength actions; In concentric (cc) muscle action, the increase in stature introduces an assessment mechanical advantage that occurs in conjunction with growth;

Leg length (ELL) significantly contributes to isokinetic  $K_{Fecc}:K_{Fcc}$ ;

Using whole body mass as a covariate may be inappropriate when examining localized muscle groups;

There are moderate to strong correlations between knee extension and flexion peak torque and fat-free mass (FFM);

The introduction of DXA preferred thigh lean soft tissue (LST) was found to be a significant explanatory variable in the development of functional extension ( $K_{Fecc}:K_{Ecc}$ ).



**Section**

**IV**

**General Discussion  
and Conclusions**

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## **Chapter VIII**

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### **General discussion and conclusions**



## **8. General discussion and conclusions**

This section intends to resume and integrate the contributions of the five studies, by summarizing the main findings and consequent practical applications, and reflecting on the implications for future research. Therefore, this research adopted a multidisciplinary approach to examine the specificity of strength characteristics in male soccer players.

### **8.1. Angle-specific KF:KE ratios**

**Isokinetic dynamometry has become a favored method for the assessment of muscle function in both clinical research and sports science.** Previous isokinetic reliability studies have focused on knee joint measuring knee flexors (KF) and knee extensors (KE) strength in adults and have shown that this tool is highly reliable (Drouin, Valovich-mcLeod, Shultz, Gansneder, & Perrin, 2004; Baltzopoulos, King, Gleeson, & De Ste Croix, 2012). Also, in the youth population, isokinetic dynamometry has the potential to be a reliable tool; however, standardized verbal instructions adapted to children and more practice before testing are needed to reduce the systematic (repeated) measurement errors (Fagher, Fritzon, & Drake, 2016).

The current Thesis incorporated two cross-sectional studies considering adult athletes. Measuring children provides researchers with additional challenges relating to variations and individual rates of growth and maturation (De Ste Croix, Deighan, & Armstrong, 2003). Adjustments are necessary for dynamometer seat and attachments, in addition to stabilization and testing procedures. Isokinetic testing of children has a test-retest variation similar to adult variation, of around 5-10% (De Ste Croix et al., 2003). Generally, it is reproducible and reliable as long as equipment and protocols are properly adapted for their body size and good habituation



procedures (i.e. training), especially during eccentric (ecc) actions (De Ste Croix et al., 2003).

Chapters 3 and 4 cross-sectional studies innovate once isokinetic interpretation considers torque values derived from the KF and KE using the same angular velocity at specific angle positions using gravity-corrected, windowed, and filtered data. Each individual curve was inspected in order to consider “true” isokinetic torques within 95% confidence interval of the angular velocity of  $60^{\circ}\cdot\text{s}^{-1}$ . The most common reported angular velocities are 60 and  $180^{\circ}\cdot\text{s}^{-1}$  (Undheim et al., 2015). Velocities  $\leq 180^{\circ}\cdot\text{s}^{-1}$  are used to test strength and  $>240$  to test endurance (Ghena, Kurth, Thomas, & Mayhew, 1991). Accordingly, angular velocities of  $60^{\circ}\cdot\text{s}^{-1}$  generally meet most requirements for validity and the need for information about muscle angle-specific performance.

**Muscle imbalances and particularly KF-to-KE imbalances have been widely suggested as potential risk factors for non-contact knee-joint injuries and Hamstring strains.** Muscle injuries are a substantial problem for soccer players (Hamstring strains was pointed as being the 3<sup>rd</sup> most common soccer injury) and constitute more than one-third of all time-loss injuries (Ekstrand, Walden, & Hagglund, 2016).

**Muscle balance at the knee joint has typically been quantified by measuring the KF-to-KE peak torque (PT) ratio.** The labeled conventional KF:KE simply indicates the degree of qualitative similarity between the KF and KE moment-velocity patterns (Aagaard, 1995). **The antagonist-agonist strength relationship for knee extension and flexion may be better described by a functional KF:KE,** once physiological knee joint movement combines ecc Hamstring muscle contraction with Quadriceps concentric (cc) action during extension function and the opposite in the act of knee flexion.

**Assessment of the KF-to-KE strength ratio at the same knee-joint angle provides a more functional relevant measurement** and offers clinical relevant

information regarding the muscular control (El-Ashker, Carson, Ayala, & De Ste Croix, 2017). The proposed isokinetic strength ratio measurements appeared to be highly reliable: functional extension ratio considering agonist PT angle (ICC=0.98; 95%CI: 0.96 to 0.99) and, functional flexion ratio considering agonist PT angle (ICC=0.95; 95%CI: 0.89 to 0.98). According to Currell and Jeukendrup (2008), the ICC is a form of correlation that can be used to assess reliability with a value of >0.9 being highly reliable. The remaining reliability indicators (i.e., TEM and %CV) also fitted the statistical sports medicine recommendations (Atkinson & Nevill, 1998).

**The ability of the muscles to control the joint is influenced by the angular position.** It was previously stated that there are statistically significant effects of angular velocity and joint angle on functional ratios (El-Ashker et al., 2017). Analysis considering torque-angle relationship provides a more robust comparison of knee-joint muscle functions (Evangelidis, Pain, & Folland, 2015; El-Ashker et al., 2017). Anterior cruciate ligament (ACL) rupture is most likely to occur near to full knee extension during a high-velocity movement (De Ste Croix, ElNagar, Iga, Ayala, & James, 2017). **Functional ratios derived from angular positions near to full knee extension show higher disparities than flexed angles.** Chapter 4 demonstrates major imbalances in near full extension angles (20-30), due to specific ecc Hamstring weakness when the joint is approaching to 0°.

**Ecc Hamstring muscle action is less effective in extended knee positions.** Current findings support previous work on male soccer players that described a variation on functional extension ratio from 0.78 compared with over 1.5 near full knee extension (Evangelidis et al., 2015). These conclusions have implications for soccer common movement patterns that place the knee in extended positions (i.e., tackling, landing, kicking). Our findings reinforce the need for using angle-specific PT to calculate the ratios and the need to observe the change in the angle-specific ratio during the considered range of motion, demonstrating compromised muscular control of the knee joint and having implications in injury risk. **Near full knee extension, angular positions represent a range where the injury is most likely to occur.** Soccer common movement patterns, such as landing that occurs with a knee

angle of less than 30° of flexion, places a greater load on the ACL (Myers & Hawkins, 2010).

In line with previous studies (El-Ashker et al., 2017; De Ste Croix et al., 2017), focused on sex differences related to isokinetic strength, this information reinforces the need to focus on increasing Hamstring ecc strength, replicating soccer-specific landing movements. Together with the existing literature, current outcomes might improve current screening and training methods and be helpful in rehabilitation programs; identifying the soccer standard function of the knee joint; and, determining cut-off values that whether for an athlete safely return to sport.

Longitudinal studies considering youth soccer players are needed to further understand curve trajectories of strength development with a focus on intra-individual or ontogenetic allometric coefficients ( $k'$ ) derived from multilevel multiplicative models that may be more appropriate for the analysis of these traits during growth.

## **8.2. Modelling strength development during pubertal years**

With the objective of studying the three expressions of muscular actions, longitudinal design approach was carried out to study the developmental changes associated with strength. Using multilevel modelling, it is possible to model not only the within-subject strength actions variation with time but also the variation between subjects while simultaneously accounting for other explanatory variables such as age, biological maturation, body size (whole and appendicular) and composition, and training (Chapters 5-7).

When determining isokinetic strength among pediatric population, age, sex, maturation and body size are of critical importance (Mohtadi, Kiefer, Tedford, & Watters, 1990; De Ste Croix et al., 2003). Most of the cross-sectional available data regarding isokinetic dynamometry have demonstrated a significant increase in

strength with age (Andersen, & Henckel, 1987; Sunnegardh, Bratteby, Nordesjo, & Nordgren, 1988; Kanehisa, Yata, Ikegawa, & Fukunaga, 1995; De Ste Croix, Armstrong, & Welsman, 1999; Gur, Akova, Punduk, & Kucukoglu, 1999; Bogdanis & Kalapotharakos, 2016; Chiamonti Bona et al., 2017). De Ste Croix et al. (1999), concerning youth male soccer players, noted an increase in absolute strength of KF (285%) and KE (314%) from the age of 9 to 21 years. The same significant increase in isokinetic knee extension and flexion was presented in boys aged 7-18 years (Kanehisa et al., 1995). Age, *per se*, exerts an independent effect on strength development (Beunen & Thomis, 2000). Chronological age (CA) has been shown to have a strong effect on muscular actions strength development, besides the rates of growth and maturation variation. These findings contradict those reported by De Ste Croix, Armstrong, Welsman, and Sharpe (2002) 10-14-year-old non-athletes. Through the use of multilevel modelling. **CA was a significant explanatory variable once body size, body composition, and maturation were taken into account.**

There are few studies that have examined the effect of maturation on isokinetic strength (Blimkie & Sale, 1998; De Ste Croix et al., 2002). Only one study has considered athletes (Carvalho et al., 2012). To our knowledge, no studies have used the biological age to classify the maturity status of adolescent soccer players. The inclusion of this predictor on predictive models is controversial. Isometric findings of our study (Chapter 5) are in agreement with isometric studies that have indicated non-significant maturational effects on strength development (Maffulli, King, & Helms, 1994; Blimkie & Sale, 1998). The lack of significant effect of skeletal maturity status on regression models extended to cc muscular actions (Chapter 6). Using alternative indicators to the reference skeletal age method, stage of puberty did not explain developmental trajectories of isokinetic leg strength in non-athletes (De Ste Croix et al., 2002), and developmental changes in the standing long jump were also independent of maturity status based on predicted age at peak height velocity (Deprez et al., 2015), in youth soccer players aged 11-14 year. These results should be interpreted cautiously since predictive equations present limitations.

In a review work, Beunen and Thomis (2000) stated that biological maturation explains significant proportions of the variation in strength. In a longitudinal analysis considering eighty-nine school boys of contrasting maturity status, early maturing boys had higher muscular strength compared with late maturing boys between 11-17 years (Jones, 1949). The analysis of the functional relationship (ecc:cc and cc:ecc) results of our research (Chapter 7) confirmed maturity status has been significant on knee joint function regression models. According to Lefevre et al. (1990), this performance advantage associated with early maturation disappears at adult age. At the age of 30, late maturers performed better on lower limb explosive strength (vertical jump).

Previous longitudinal studies have indicated strong relationships between body size (i.e., stature and body mass) and isokinetic lower-limb strength (Sunnegardh et al., 1988; De Ste Croix et al., 1999; Kanehisa, Ikegawa, Tsunoda, & Fukunaga, 1994; De Ste Croix et al., 2002). Blimkie and Sale (1998) suggested that **stature might not play a major role in the development of isometric strength actions**. The same results were found in our Chapter 5. This does not appear to be the case for cc actions as it has been confirmed that stature influences isokinetic knee extension (Chapter 6). This finding is in accordance with a longitudinal study with 10-14-year-old boys and girls (De Ste Croix et al., 2002). **The increase in stature introduces an assessment mechanical advantage that occurs in conjunction with growth**. Isokinetic muscle strength is measured in torque, which encompasses moment arm (mechanical advantage) (De Ste Croix et al., 2003). The increase of femur, tibia and fibula lengths leads to a stretch of the limb muscles providing a stimulus for muscle development, which is most important for isokinetic assessment that is dependent on muscle moment arm length (De Ste Croix et al., 2003). Only the last study (Chapter 7) considered estimated leg length (ELL) as a study variable, and results confirmed that **this estimation significantly contributed to isokinetic KFecc:KFcc** across adolescence in youth soccer players. This finding is corroborated by Kanehisa et al. (1994) results, where cc knee PT was significantly correlated ( $r=0.72-0.83$ ) with thigh length in boys.

To consider body mass as a predictor is conflicting since strength development may not follow the same profile in all muscle groups (De Ste Croix et al., 1999). **Using whole body mass as a covariate may be inappropriate when examining localized muscle groups** (i.e., thigh muscles) such as isokinetic knee joint strength where muscle size may be a more appropriate covariate (Nevill, Holder, Baxter-Jones, Round, & Jones, 1998).

During the growth spurt, strength increases coincide with changes in fat-free mass (FFM) (Malina, 1975; De Ste Croix et al., 2003). **Studies considering isokinetic strength have reported moderate to strong correlations between knee extension and flexion peak torque and FFM** (De Ste Croix et al., 2003; Camic et al., 2010). Supported by a longitudinal analysis (De Ste Croix et al., 2002), the multilevel regression model included skinfold thickness as a significant explanatory variable in the development of peak flexion torque of the knee. Although the technology for estimating body fat has expanded considerably, each protocol has its limitations and underlying assumptions. In spite of their limitations, the use of skinfold thickness to estimate absolute and relative fatness and fat-free mass has a long tradition in the sports science (Coelho-e-Silva et al., 2010). Limitations of the prediction protocol based on skinfolds are noted in the discussion sections. Studies from Chapters 5 and 6 considered FFM calculated according to the validated skinfold thickness by Parizkova (1977). The original regression model was highly correlated ( $r=0.896$  for boys aged 9-12 and  $r=0.916$  for boys aged 13-16) with body density (hydrostatic weighting and estimation of residual air in the moment of weighting by the nitrogen dilution method).

Considering FFM as a longitudinal predictor was previously remarked for explosive lower limb power from childhood to adulthood in high-performance soccer players (Deprez et al., 2015). The effect of FFM that correlates with “muscularity” of the soccer players seemed significant in jumping performance. Muscle mass distribution varies at different body sites, about 40% of total muscle mass is located in the lower extremities at birth, increasing to about 55% at sexual maturity (Malina, 1969). Changes in muscle mass distribution contributed to higher adjusted PT FFM

in 14- to 18-year-old wrestler athletes compared with younger age groups (Weir, Housh, Johnson, Housh, & Ebersole, 1999). Little is known regarding the relationship between regional muscle cross-sectional area and FFM during growth. Taking this into account, Chapter 8 included a measure of lower limb mass obtained from Dual-energy X-ray Absorptiometry (DXA). **The introduction of DXA preferred thigh lean soft tissue (LST) was found to be a significant explanatory variable in the development of functional extension (KFecc:KEcc).**

### **8.3. Implications and transfer of knowledge**

The main purpose of this Thesis was to gain more understanding of the relationship between (the development of) strength and body size and composition and biological maturation, using a multidisciplinary approach. Considering the variation in methodology and sampling in studies presented on this Thesis, in addition to the conclusions previous stated (segment 8.2), practical implications for researches, clinicians, coaches, physical trainers, players, clubs, soccer federations and manufacturers can be derived:

#### Researches and clinicians

The antagonist-agonist strength relationship for knee extension and flexion may be better described by a functional KF:KE of ecc Hamstring to cc Quadriceps muscle strength and vice-versa. The ability of the muscles to control the joint is influenced by the angular position. The assessment of the KF to extensors strength ratio at the same knee-joint angle provides a more functionally relevant measurement. Using whole body mass as a covariate may be inappropriate when examining localized muscle groups. Our work allowed quantifying the impact of the principal modifiable determinants of strength parameters. Multilevel modelling has the potential to provide useful information in the explanation of inter-individual differences at a certain age and probably more important to predict and explain changes over time, allowing a critical interpretation of variation within and between individuals. The

development curves make it possible, when compared with performance curves. This allows coaches and trainers to assess an individual's performance relative to these curves.

#### *Coaches and physical trainers*

By applying the curves, trainers and coaches can determine if a player is performing above or below average for his age. Functional ratios derived from angular positions near to full knee extension show higher disparities than flexed angles. Ecc Hamstring muscle action is less effective in extended knee positions. These angular positions represent a range where the injury is most likely to occur. Stature might not play a major role in the development of isometric strength actions. In cc muscle action, the increase in stature introduces an assessment mechanical advantage that occurs in conjunction with growth. ELL significantly contributes to isokinetic  $K_{Fecc}:K_{Fcc}$ . There are moderate to strong correlations between knee extension and flexion peak torque and FFM. The introduction of DXA preferred thigh LST was found to be a significant explanatory variable in the development of functional extension ( $K_{Fecc}:K_{Ecc}$ ).

#### *Players, clubs, and soccer federations*

The resulting equations permit to acquire this information in a safe and cost-effective and manner. If cubs' philosophy is to pursue talent development, they should invest in specialized staff members, who could put what is known from literature into practice. Given the crucial adolescence period in the physical development of young soccer players, it seems extremely important that both clubs and federation supervise their players' development. To create a follow-up database with players' information (anthropometrical characteristics, test outcomes, players history, injuries), could give a holistic view of each player.



### Manufacturers

During the research years of the present Thesis, the practice on the evaluation of isokinetic strength using the dynamometer led us to develop and patent an apparatus (in progress: Appendix 1). As described, this tool will help with joint identification and calibration, as well as facilitating reactive evaluations (leverage the 10% torque-adjusted binary value to start the movement). Currently, it is submitted as a national patent, but the main goal is to reach international manufacturers and to improve available systems.

## **8.4. Challenges for future research**

Specific limitations of the five studies were individually considered in respective Chapters. This topic aims to identify general concerns regarding the collective work performed until now and to integrate what we already know and achieved, pointing out future research.

Firstly, our predictive models need to be validated in different samples (e.g., in females, other ethnic groups, different sports modalities or specific populations of people with varying anthropometric characteristics) and considering a wider matrix of predictors. Secondly, longitudinal or mixed longitudinal studies of growth and performance of female adolescents athletes are needed.

Few studies appear to have employed electromyography to examine electromechanical efficiency in children and future work is needed to understand the influence of qualitative changes in muscle during growth and maturation regarding isokinetic performance. The percentage motor unit activation of muscles associated to the age effect in KF and KE strength production should be considered to understand neural drive.

As regards cross-sectional data, allometric scaling (log-linear regression) is considered the most appropriate approach for portioning body size effects from a physiological variable or performance. Therefore, further evaluation of appropriate indexing variables for knee joint isokinetic muscular actions in youth is needed. This will allow examining the adequacy of allometric model structures for scaling knee joint isokinetic muscular actions; and, in addition, to explore the independent and combined effects of chronological age, biological maturation, and different body descriptors to explain variability in knee joint isokinetic muscular actions.

Due to the internal rotation of the hip, causing knee valgus, the risk of injury in women is two times greater than in men, especially in sports that require rotational movements. The functional ratios reflect the magnitude of the torque differences between the concentric and eccentric portions of the torque-velocity curve. A more rigorous examination of these ratios is required to examine whether it is higher in females compared with males.

The current Thesis provides original material and stimulates further studies to offer sound practical applications for coaches. Training variables were quantified (frequency and volume). However, it is necessary to include some contextual information regarding the training quality (i.e., training load) of the participants and to investigate how these contextual aspects might influence the data analysis. In fact, training youth sports is very crucial and several issues have to be addressed. Future work could profit from considering commentaries and recommendations on youth sports to better highlight the relevance of strength training in youth soccer.

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# Appendix

# A

**Patent**

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# **A. JOINT AMPLITUDE EVALUATION DEVICE**

**2018-1121FP**

## **Abstract**

This invention falls within the area of devices for dynamometers in the measurement of muscular strength, in particular, it concerns a device for measurement and angular calibration. It is the object of this invention, a device for evaluation of the innovative articulation amplitude, which performs a calibration and angular measurement composed of a screw (1) attached to a face of a head (2) with a cylindrical shape, the other side of the head (2). It features a light source (3) and a goniometer (4) and its curved surface contains a switch (5) and a battery (6).



**Appendix**

**B**

**Curriculum Vitae**

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## **B. DeGóis<sup>®</sup> curricular platform**

<http://www.degois.pt/visualizador/curriculum.jsp?key=3186345345964014>