Isometric mid-thigh pull testing in professional footballers: validity, reliability, and correlation analysis with external loading during official matches

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I declare this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa and was also authorized by the Faculdade Motricidade Humana's ethics committee. The researchers involved in this project have no conflicts of interest.

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This is just the beginning of something greater. And remember, "consistency is the key to success".

Abstract

INTRODUCTION: Understanding the maximum strength of football players is considered essential for optimizing and maintaining individuals for high level sports performance. In this regard, the mid-thigh isometric traction test (IMTP) has been proposed to assess the overall maximum strength of football players.

OBJECTIVES: This thesis aimed to achieve four objectives, the first being: 1) examine the concurrent validity between two modalities of IMPT testing equipment in healthy individuals: i) with a force platform at the foot; and ii) with a force cell next to the handle bar. The second being: 2) determine if there is a learning period in taking the IMTP test between the first four testing sessions among professional footballers, examining the inter-session reliability between the first two similar sessions. The third being: 3) to verify whether the IMPT peak force is altered following football matches; and, lastly: 4) examine whether the changes in IMPT peak force 48h following matches is related with different external loading parameters experienced by the players during the match.

METHODS: For objective 1, one experimental session was conducted with healthy individuals (n=24); and for the remaining objectives, a total of 40 footballers from a professional football team were recruited, and who participated in IMPT testing sessions. External loading parameters were quantified during the matches using a GPS tracking system worn by the footballers.

RESULTS: 1) A low concurrent validity was observed between the IMPT testing equipment assessments [ICC = 0.47 (95% CI = -0.21- 0.79), CV = 10.8% (95% CI = 6.88 – 14.8%)]; whereas, a lower IMTP peak force was observed for the testing executed with the force platform (1693.9±112.5 N) compared with the force load cell test (1880.3±156.5 N, p<0.001). 2) Significant differences were found between the first (1843.6± 333.7 N), and second (2008.1± 397.4 N, p= 0.002), the first and third (2143.6± 454.8 N, p<0.001), and the first and fourth (2226.9±442.2 N, p < 0.001) IMTP testing sessions. No significant differences were found between the second and third sessions (p=0.085), and the third and fourth sessions (p= 1.000). Good inter-session reliability was observed between the second and third testing sessions (ICC = 0.84, standard error of measurement of 218.1± 308.4 N). 3) No statistically significant differences were found in both samples (p = 0.744 and p = 0.520). 4) A moderate and negative correlation was found between the IMTP peak force before matches and the footballer's frequency of "accelerations" (r= -0.501 and p=0.048), and a positive correlation was observed between the IMPT peak force before and after matches (r= 0.738 and p<0.001). No other significant correlations were found.

CONCLUSIONS: 1) The IMTP peak force outcome depends on the equipment used, with higher IMTP values obtained using a load cell close to the hands; 2) At least two separate familiarization sessions are necessary for professional footballers to achieve a reliable IMPT assessment; 3) The IMTP performance is unlikely to be altered 48h after football matches compared to the IMPT performance 48h before the matches; and 4) The IMTP assessments before and after the matches do not seem to be correlated with the different external loading parameters exerted by footballers during official matches.

Keywords: peak force, force platform, portable platform, load cell, maximum force, GPS, neuromuscular fatigue, strength, recovery, performance.

Resumo

INTRODUÇÃO: Compreender a força máxima em jogadores de futebol é essencial para otimizar e manter o desempenho desportivo individual. Nesse sentido, o teste *isometric mid-thigh pull* (IMTP) foi proposto para avaliar a força máxima geral nos jogadores de futebol.

OBJETIVOS: Esta tese visa atingir quatro objetivos, sendo o primeiro: 1) examinar a validade concorrente entre duas modalidades de equipamentos de teste IMTP em indivíduos saudáveis: i) com uma plataforma de força nos pés; e ii) com uma célula de força próxima das mãos. O segundo é: 2) determinar se há um período de aprendizagem na realização do teste IMTP entre as quatro primeiras sessões para jogadores profissionais de futebol, examinando a confiabilidade inter sessões nas duas primeiras sessões. O terceiro: 3) verificar se o pico de força do IMTP é alterado após os jogos de futebol; e, por último: 4) examinar se as mudanças no pico de força no IMTP 48h após os jogos estão relacionadas com diferentes parâmetros de carga externa obtidos pelos jogadores durante o jogo.

MÉTODOS: Para o objetivo 1, foi realizada uma sessão experimental com indivíduos saudáveis (n=24); e para os restantes objetivos foram recrutados um total de 40 futebolistas de uma equipa de futebol profissional, que participaram em sessões de testes no IMTP. Parâmetros de carga externa foram quantificados durante os jogos utilizando um sistema de GPS usado pelos jogadores.

RESULTADOS: 1) Observou-se baixa validade concorrente entre as avaliações no equipamento IMTP [ICC = 0,47 (IC 95% = -0,21- 0,79), CV = 10,8% (IC 95% = 6,88 – 14,8%)]; também se observou um menor pico de força IMTP para o teste executado com a plataforma de força (1693,9±112,5 N) em comparação com o teste da célula de carga de força (1880,3±156,5 N, p<0,001). 2) Foram encontradas diferenças significativas entre a 1ª (1843,6± 333,7 N) e a 2ª (2008,1± 397,4 N, p= 0,002), e entre a 1ª e 3ª (2143,6± 454,8 N, p<0,001) e entre a 1ª e 4ª (2226,9±442,2 N, p < 0,001) sessões de teste no IMTP, mas não entre a 2ª e 3ª sessões (p=0,085), e a 3ª e 4ª sessões (p= 1,000). Boa confiabilidade inter sessões foi observada entre a 2ª e 3ª sessões de teste (ICC = 0,84, erro padrão de medição de 218,1± 308,4 N). 3) Não foram encontradas diferenças estatisticamente significativas em ambas as amostras (p = 0,744 e p = 0,520). 4) Observou-se uma correlação moderada e negativa entre o pico de força do IMTP antes dos jogos e a frequência de "acelerações" dos futebolistas (r= -0,501 e p=0,048), e uma correlação positiva foi observada entre o pico de força no IMTP antes e depois dos jogos (r= 0,738 e p<0,001). Não foram encontradas outras correlações significativas.

CONCLUSÕES: 1) O resultado do pico de força no IMTP depende do equipamento utilizado, com maiores valores de IMTP obtidos utilizando uma célula de carga próxima às mãos; 2) Pelo menos duas sessões separadas de familiarização são necessárias para que os jogadores de futebol profissional alcancem uma avaliação confiável do IMTP; 3) O desempenho dos jogadores no teste IMTP parece não sofrer alterações 48h antes e depois dos jogos de futebol; e 4) As avaliações no IMTP antes e depois dos jogos não parecem estar correlacionadas com os diferentes parâmetros de carga externa obtidos pelos futebolistas durante os jogos.

Palavras-chave: pico de força, plataforma de força, plataforma portátil, célula de carga, força máxima, GPS, fadiga neuromuscular, força, recuperação, desempenho.

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List of abbreviations

IMF Isometric maximum force

IMTP Isometric mid-thigh pull

NF Neuromuscular function

MVC Maximum voluntary contraction

MVIC Maximum voluntary isomeric contraction

N Newton metric

GPS Global Positioning System

DOMS Delayed onset muscle soreness

CK Creatine Kinase

SEM Standard error of the mean

ICC Intraclass coefficient of correlation

CV Coefficient of variation

Vel_1 Velocity zone 1 (< 16 Km/h)

Vel_2 Velocity zone 2 (16 km/h to 19.8 km/h)

Vel_3 Velocity zone 3 (19.8 km/h to 25.1 km/h)

Vel_4 Velocity zone 4 (>25.1 Km/h)

Peak_Force_Abs_PRE Maximum absolute peak force before the game

Peak_Force_Abs_POS Maximum absolute peak force after the game

Peak_force_loss Percentage of peak force loss

Total_distance Total distance covered during the game

Distance_Vel_1 Total distance covered on Vel_1 during the game

Distance_Vel_2 Total distance covered on Vel_2 during the game

Distance_Vel_3 Total distance covered on Vel_3 during the game

Distance_Vel_4 Total distance covered on Vel_4 during the game

Accelerations Number of accelerations

Decelarations Number of decelerations

Time_Played Total of time played

Time_played_Total_distance Density of game played

CHAPTER I: Introduction

1.1 Contextualization

Association Football (*i.e*., football or "soccer") is a sport wherein participants experience intermittent degrees of maximum physical effort. The variability of effort may involve different activities, such as, short to long sprints, bouts of walking, running, jumping, kicking and heading, throughout any particular match. Improving the performance of footballers for the higher intensity activities requires increasing their overall maximum strength, particularly in the lower limbs [1]. Football is, perhaps, the sport with the widest number of participants in the World, recreationally and professionally. From a professional perspective, improving a team's domination on the field of play especially requires enhancing the physical attributes of individual athletes, most notably strength and power [2].

In order to achieve this enhancement, it is crucial to develop a system that can reliably evaluate an athlete's progress in any particular strength-training program. One very important program, for football players, is lower limb strengthening. For this, testing the maximum number of repetitions or a singular maximum (one-rep max, 1RM) in squats is one possible way to evaluate changes in lower limb muscle strength [3][4][5]. Another promising method includes isometric mid-thigh pull (IMTP). IMTP measurements are strong indicators of potential for explosive and maximum strength under dynamic conditions in football and other sports [6][7][8][9]. Importantly, IMTP testing has advantages over the 1RM squat assessment, in that it has a lower risk of injury, only requires minimal experience to execute, is relatively simple to perform, strongly correlates with dynamic performances, and is highly reliable when replicated [6] [10][11].

Following a football game, muscle fatigue in a player is expected to be at both the level of voluntary activation, requiring recovery within 48h postgame, and at the level of maximum voluntary contraction, requiring up to 72h of recovery [12]. Based on evaluations involving half squats (having moderate correlation with IMTP [7]), investigators showed that players having greater strength in their lower limbs had reduced levels of creatine kinase (CK) (a key metabolic enzyme associated with skeletal muscle contraction and relaxation), indicating lower muscle strain at 48h postgame, than players having lessor lower limb muscle strength [13].

Based on this finding, it is possible to hypothesize that higher strength in an IMTP test pregame will show less neuromuscular fatigue 48h post-game. However, there is one published study showing that after a period of long-term or high-intensity strength training (not from playing football), values of IMTP tests showed no difference before and after exercise [14]. Other than this latter report, there is no further literature examining fatigue/muscle fatigue ratios 48h post exercise.

In view that the subject area of muscle strength/recovery as it relates to peak strength is unclear, the present research proposes to provide further understanding on this subject by examining whether athletes who have more minutes of game time, or overall higher levels of game effort (sprinting, distance covered, etc.), exhibit either augmented or reduced maximum peak strength post-game, based on IMTP testing.

In this regard, the present thesis aimed to first determine the validity of using a force platform or a force portable platform having a load cell to measure force, and secondly the reliability of the IMPT test and what level of familiarity athletes needed with the test prior to collecting valid analytical data. Thirdly, it will examine how peak strength varies among athletes depending on their amount of game effort (time played, *etc*.) throughout a football season. And, fourth, what types of changes occur, gain or loss of strength, if any, based on IMTP tests between pre-game and post-game (48h later).

1.2 Objectives and hypotheses.

This investigation has the following objectives and hypotheses:

- **Objective 1**: Examine the concurrent validity between two modalities of maximal force quantification in the IMPT test: i) with a force platform, where the force sensor is at the feet; and ii) with a portable force-cell, where the force sensor is next to the handle bar pulled to measure force. We hypothesized IMTP measurements are the same between the force platform and the portable force cell platform.
- **Objective 2**: Compare the IMPT performance between four testing sessions, and examine their inter-session reliability between the first two similar sessions. We hypothesized measuring day-to-day reliability of maximum strength using the IMTP test is high following at least one familiarization session.
- **Objective 3**: Determine if the IMTP performance is altered 48h following an official football match in professional footballers. We hypothesized there is a difference in maximum strength values between pre- and post-game based on IMTP measurements after familiarizing subjects to the test.
- **Objective 4**: Determine whether there are any correlations between IMTP performance 48h before and 48h after matches, over the course of a football season, and the different external loading parameter that can be extracted from the GPS tracking system (*e.g.* total distance run). We hypothesized there is a decrease in peak force values obtained in the IMTP test, which were influenced by greater external load variables, 48h after a game.

CHAPTER II: Literature review

2.1 Importance of maximum strength in team sports

Maximum force is defined as the highest value of force a neuromuscular system produces against immovable resistance over a set point in time. Regardless of the time factor, this force is considered the base component influencing the manifestation of all other forms of force [15]. In this regard, it is possible to determine if muscle strength at a particular point in time of an athlete is related to the athlete's ability to optimize strength usage over time. This optimization is a major contributor to the general performance of an athlete, such as the rate of force development and external mechanical power. Optimizing sports performance skills, such as jumping, sprinting, and changing direction, is also associated with increasing potentiation effects, like strength, and decreased injury rates, exhibited by force-time variables when measured by IMTP [16][17][18]. Isometric strength training is less fatiguing than dynamic strength training and is helpful in maintaining or augmenting an athlete's performance. In addition, this type of training is useful for monitoring related types of performance in various sports [19].

The development of muscle strength is supported by a combination of neural and morphological factors, including muscle cross-sectional area and architecture, muscle-tendon stiffness, recruitment and synchronization of motor units, and neuromuscular inhibition. Thus, weaker/less skilled athletes should focus on developing core strength, while stronger/skilled athletes should focus on exercises that optimize power levels, maintaining or increasing their current strength levels [20]. Power values are probably the most important parameter to consider for designing training methods to improve performance, and to promote athletic success. One of the factors behind this concept is the strong relationship between improving performance, such as sprinting, jumping, changing direction, throwing and weightlifting movements, with power. There is literature suggesting that athletes with different levels of peak power have different levels of athletic performance. Therefore, development of muscular power is a determining factor for attaining high-level performance in a spectrum of aerobic to anaerobic sports [21]. To attain peak performance, it is necessary to examine the relationship between power and speed, represented by the force-velocity curve (Figure 1). This relationship is important, because the portion of the curve showing maximum strength is where the velocity of the test individual is lowest. And *vice-versa*, where velocity is highest, force is lowest. Hence, to attain optimal performance it is important to work both in the speed zone and in the heavy loads area. Also, for improving performance, once again, one must include increasing strength levels [21].

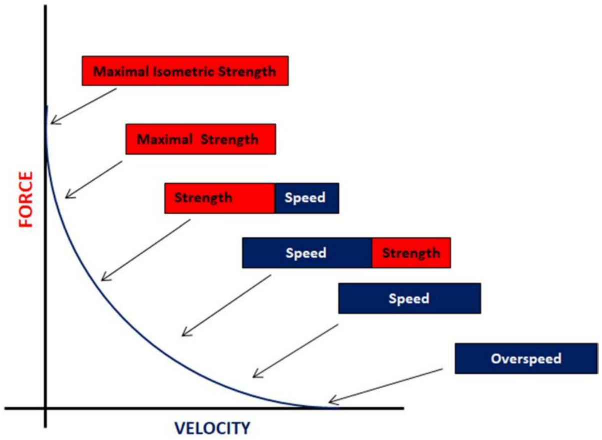

Figure 1. *Force-velocity curve* [22].

2.1.1 Recovery context

With regard to football, a sport involving momentary fatigue, there is increasing fatigue as the level of participation in a game increases. This fatigue is generally represented by a decline in muscle performance depending upon the level of activity during the game [23]. Some studies have shown that, post-game, it may take more than 72h for players to achieve pre-game levels of muscle performance, in addition to normalization of any inflammation or muscle damage, especially for high-performance athletes [24]. However, it should be noted that fatigue after a football match is multifactorial (depending on intrinsic and extrinsic factors) and is related to glycogen depletion, dehydration, muscle damage and mental fatigue. [24]. Some post match procedures have been used in football to accelerate the recovery process, such as rehydration, a specialized diet, rest and sleep, and immersion in ice water, all of which have been found to be effective [25]. When these treatment methods are not sufficient, such as when an injury occurs (for example, anterior cruciate ligament injury), it is necessary to perform an assessment of muscle damage by measuring strength using isometric tests [26]. With this type of test, it may be possible to quantify the level of decline in the capacity of maximum strength and muscle power [27].

As already mentioned, regarding the accumulation of fatigue during a match, there is a concomitant decrease in maximum muscle strength at least up to 72h post-match. This damage may also involve muscle injury obtained during play. The best method to quantify this type of debilitation to muscles post-match is by measuring maximum voluntary contraction, as this can be accurately quantified. Moreover, it is ideal to assess an athlete's fatigue by performing, at a minimum, a physical test, a cognitive or subjective test and a biochemical test. [28]. We can see in the following table (Figure 2) that maximum voluntary strength appears to be one of the markers/tests having greatest utility in representing level of muscle fatigue:

Marker	Fatigue	EIMD	Training recovery
Vertical Jump	✓	?	✓
Maximal voluntary strength	✓	✓	✓
Sprint	✓	?	✓
RSA	✓	?	✓
Aerobic tests	✓	✗	✓
Skill performance	?	?	?
Subjective markers	✓	✓	✓
Cognitive markers	✓	✗	?
Lactate	✓	✗	✗
Ammonia	✓	✗	✗
Urea	✓	✗	✓
Testosterone	✗	✗	✓
Cortisol	✗	✗	✓
T/C ratio	✗	✗	✓
CK	✗	✓	✓
LDH	✗	✓	✓
Myoglobin	✗	✓	✓
IL-6	✗	✓	✓
CRP	✗	✓	✓

Figure 2. *Summary of markers having potential utility to assess muscle fatigue/ performance decrease post-match* [28]. *A check (√) indicates the marker is a reliable measure of muscle performance (Fatigue, EIMD* (Exercise-induced muscle damage) *and Training recovery. An "X" represents the respective marker is unreliable.*

Remedying muscle fatigue after a football match includes active recovery (low intensity running, 65% of maximum aerobic velocity, and stretching), passive recovery (whole body vibration and immersion in cold water). These can be achieved using neuromuscular electrical stimulation and compression equipment. These procedures are described in the following table (Figure 3) [29].

Practical guidelines for enhancing recovery in soccer players			
Recovery method	**Practical recommendations**	**Duration**	**References**
Active recovery			
Low-intensity aerobic activity	12-min of submaximal running at 65% of MAV	>10 min	(55,56,68)
Stretching	3 × 30 s bilateral static stretching the hamstring, quadriceps, gastrocnemius, and adductor muscles	12 min	(55,56,68)
Passive recovery			
Whole-body vibration	2 × 60 s stretching and massage lower limb exercises with a superimposed vibration stimulus	>5 min	(39)
Cold water immersion	8–10 min at 10–15°C or 4 × 4 min immersion; immersion to the iliac spine level	5–10 min	(6,21,26,59)
Neuromuscular electrical stimulation	Frequency of 1 Hz; current of 27 mA; pulse width of 140 microseconds; intensity strong enough to elicit visible contractions; 20 min	20 min	(67,68)
Compression garments	Compression tights during or/and training or competition	Until next training session	(71)
MAV = maximal aerobic velocity.			

Figure 3. *Most frequently employed and recommended methods for muscle fatigue recovery in football* [29].

When discussing a player's ability to return to play after a hamstring injury, one of the main criteria proving to be most relevant, and being most studied, is strength (Figure 4).

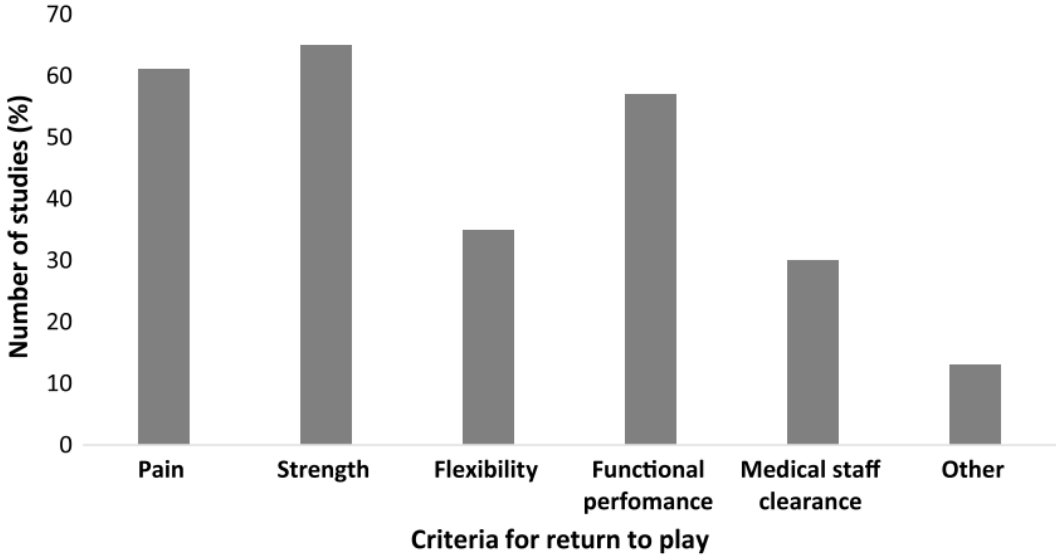

***Figure 4**. Criteria for deciding when an athlete can return to sports practice after a hamstring injury [30].*

With regard to measuring strength many authors have observed that the IMTP test performed on a portable platform is highly applicable for determining a player's muscle recovery from injury [31]. Additionally, strength training is essential for reducing sports injuries by one-third and decreasing almost a half of injuries that would incur resulting from excessive activity [32]. Priority in the recovery process must be based on the basic principles of training, nutrition, hydration, sleep, hygiene and proper rest [33].

2.2 Isometric mid-thigh pull (IMTP) assessment: characteristics, and reproducibility

It is important to be able to evaluate whether an athlete's muscle performance is improving over the course of the training period. Having an accurate and uncomplicated method to assess levels of an athlete's performance allows the training process to be well managed, while possibly enhancing the athlete's performance [34]. The variables a sport scientist must take into account must be specific to the athletic action in question [12][35]. By using IMTP to assess peak strength over a training period allows determining which squatting/ hang-clean position [6] should be maintained throughout all sessions (which should always be the position the subject considers most comfortable for the greatest production of strength). Prior to the lift, the position of the subject for a test should be feet at hip or shoulder width, the bar positioned to mid-thigh height with the torso facing forward, the spine in a neutral position, the knees bent at ~140 degrees, and the angle at the hip, between the torso and thigh, ~135 degrees [12][10]. However, some authors report that the hip and knee angles do not influence the kinetic variables when the position of the bar was maintained at a constant height. These same authors concluded that one should observe changes in >1.3% in peak isometric force, >10.3% in maximum rate of force development, >5.3% in impulse at 100 milliseconds, >4.4% in impulse at 200 milliseconds, and >7.1% in impulse at 300 milliseconds, irrespective of posture [36].

The IMTP test is as reliable and valid for assessing changes in lower limb muscle strength as an isokinetic test (*e.g.,* 1RM squat) [37][31], including changes in muscle mass volume (more precisely in the dominant lower limb, the *vastus lateralis*) and correlates well with peak bilateral strength in the IMTP test [38]. This test involves the subject pulling a bar to a position that is equivalent to the squatting positioning of a second pull of a clean-lift (this portion of the clean pull produces the highest bar velocity, ground reaction force and power output, when compared with the other two clean-lift positions) and is held in that position, at maximum strength, for 2-3 seconds [39]. According to published results, the various cohorts of football players already tested using IMTP show highly consistent and reproducible results [10]. This test is relevant to other performance indicators and is a recommended test to monitor and evaluate professional football players. The results of this test help direct the type of intervention(s), that might be indicated, by the strength and conditioning coaches [40].

2.3 Isometric mid-thigh pull familiarization

Current literature provides varying viewpoints on the procedure for familiarizing the test subject for IMTP testing. The consensus is that prior to IMTP testing at least one familiarization session is needed. This session entails practicing the IMTP protocol until the subject is comfortably acquainted with the technique and the researcher is confident with compliance of the test subjects [12][31]. Familiarization sessions are necessary to ascertain the pull position for increasing force production and stabilization. This can differ with different positions. For example, an upright body position is appropriate for general use, while specific body angles/position can be tailored for differing sports requirements [41]. In a study with elite youth football players, a minimum of four familiarization sessions was required to attain reliable data for the IMTP test [42]. Other investigations also concluded more than one session might be required for familiarization to IMTP testing, as biases were detected between the first two sessions [10][43]. Thus, to date, it appears there is not a consensus regarding the number of familiarization sessions required, to obtain reliable and reproducible IMTP test data.

2.4 Measurement/quantification of muscle fatigue at 48h, based on maximal strength

Muscle recovery is very important in the recovery of athletes, in addition to muscle maintenance, and for increasing performance [44]. For this purpose, it is necessary to constantly evaluate and establish a method for quantifying the status of players. Declining changes in speed, repeated-sprint ability and maximal strength are indicators of risk of injury. They can also be used to apply training techniques to promote an increase in performance. Thus, it is important that coaches require a consistent and adequate weekly level of training in order to protect the athlete from exercise-derived injury, pre-season and during the playing season [45].

With professional football players, there can be a reduction in capacity for maximum voluntary contraction (MVC) and sprint speed after a match. However, 48h post-match, both capacities return to near normal in most cases. However, there are reports of impaired neuromuscular function, in some cases after 72h [46] following a training session. This impairment can result from a combination of central, peripheral and perceptual factors [33][47]. Apparently, fatigue at the level of the central nervous system has the greatest effect on the decline in these capacities (MVC and sprint) [47]. This fatigue likely has a negative impact on other explosive-type playing actions typically involved in a football match, such as sprinting, acceleration, kicking, *etc*. [48]. There is already a study of young players, showing a relationship between IMTP performance and neuromuscular fatigue. The IMTP test in this case served as an indicator of whether a player was prepared for competition/training [9]. Maximum voluntary isometric contraction (MVIC) may also be useful in assessing changes in neuromuscular function of lower limbs in male and female athletes [49].

2.5 Variables and effects of game load

It is important to know which external and internal load variables of a match should be considered to plan training intensities applicable to specific positions of the players. The administered load must take place one day prior to the match (match day minus one, MD-1) and one day post-match (MD+1), to compensate for absence of muscular activity under match competition. Application of the test must be synchronized with weekly training loads of all team members with the exception of the starters [50]. One must take into consideration, throughout the entire training period, the variables determining intensity (distance covered at high intensity running: >19.8 Km/h) and number of accelerations and decelerations according to each player's position [51]. These variables are the best indicators between pre- and post-match changes in biochemical and neuromuscular responses (MD+1), in addition to changes in levels of CK [52].

Additionally, player load and metabolic power are variables that can possibly be used to monitor external load quantification [53]. It should also be noted that weeks in which there is a lower external load and lower number of training sessions, prior to a match, can be reflected by a more positive performance on game day [51]. This was verified by a study showing that playing against top-level teams (before and after) and after losing a match, players had a higher training volume. But, there was a decrease observed in higher intensity training, before and after, playing against top level teams, and an increase after a home game or preparing for an away game [54]. Acceleration and deceleration variables, in addition to information provided by more commonly used variables such as speed and distance, contribute 7-10% and 5-7%, respectively, for total player load of all positions, [55][56]. A new index has been introduced termed "workload efficiency" for predicting match performance based on internal and external loads [57].

2.6 Relationship between GPS and peak strength

Technologies for capturing and analyzing a football player's physical levels of exertion during a match have been growing in number and increasingly improved (*e.g.* GPS, Prozone – STATS [58], OPTA) [59]. Among the existing types of GPS tracking devices having greater reliability and accuracy are the 10 Hz devices, overcoming many of the limitations of the others. Devices with higher than 10 Hz possess no added value [60]. Information provided by such GPS devices can greatly facilitate management of player performance. This is possible as internal and external load can be measured by registration of acceleration and deceleration during a training session. This provides information regarding level of hamstring fatigue and reduced force production, both of which are indicators of a higher risk for injury [61]. It has been shown high levels of sprinting are an important indication of match-related lower limb muscle fatigue in young males [62]. Moreover, GPS monitoring allows identification of the relative demands placed on each player involved in training and competition. This monitoring facilitates ability to establish levels of training intensity and recovery time [63]. It is important to have this knowledge, at a minimum of 72h post-match, in order to re-establish cognitive and biochemical normality. Managing such factors as delayed onset muscle soreness (DOMS) and muscle damage to the hamstring muscle (eccentric and/or isometric muscle action), counter movement, jump performance, and CK, are important in order for a player to achieve peak performance on game day [63]. To date, a clear relationship between GPS information and peak strength has yet to be established. But some studies suggest the use of GPS data can provide clues regarding loss of hamstring strength [61].

CHAPTER III: Materials and methods

3.1 Study design

First, we attempted to find out if there were differences in quantification of maximum force between different platforms (force platform versus portable force-cell platform). After performing a warm-up (*i.e.*, 20 reverse lunges, 20 jumping jacks, 10 squats and 10 hip thrusts), the participants performed three maximum attempts of the IMPT test using each of the different platforms, in random and balanced order. The test was performed according to the execution technique usually described in the literature [10][12], with the bar being placed at a comfortable height for the individuals, and maintained at that level for all tests. The best attempt of each of the two platforms was statistically analyzed for any significant differences ($p<0.05$) (hypothesis 1).

Second, the study-design (Figure 5) of our research was cohort-based and included footballers (>18 years-old) from a Portuguese Second Division professional football team, Amadora. Individuals were tested between December 2021 and May 2022. Forty footballers participated in the tests during this timeframe. Before the tests were carried out, measurements were taken of the lower limbs (femur length + tibia length), in order to understand at what percentage of the height of the leg the bar was placed. This sample size was sufficient [Correlation ρ H1 = 0.4; α err prob = 0.05; Power (1-β err prob) = 0.80] for this investigation, considering an effect size of 0.2 and a statistical power of 0.8. IMTP testing was performed on athletes who did not present any type of injury at the time of testing. Testing was conducted at the team facilities, performed two days before and two days after football matches (Table 1). When not possible, due to logistical or sporting issues, testing was conducted within the window of scheduled test-days and hours, as close as possible according to scheduled matches. The first three test sessions took place before the first three matches and examined any changes in IMTP measurements, including those during the familiarization process (hypothesis 2). The second and third IMTP testing sessions, before matches, were used to examine objective 2, and took place prior to matches in order to standardize *per diem* reliability/variability of the testing process. The remaining testing sessions were used to test hypothesis 3, if changes occurred in maximum strength in players between pre- and post-game. Two examinations of changes in a player's IMPT maximum force were analyzed based on first game after familiarization (third game) and all games played after the third game (first test session). Lastly, to test objective 4, we attempted to understand if certain correlations occurred between external load from the game day (through GPS variables) with loss/change of peak force absolute PRE and POS, with our IMTP test.

Table 1. Schedule of IMTP test sessions.

Test number	**Pre-match test date** (dd.mm.yyyy)	**Match date** (dd.mm.yyyy)	**Post-match test date** (dd.mm.yyyy)
1	12.12.2021*	13.12.2021	15.12.2021
2	17.12.2021	19.12.2021	21.12.2021
3	25.12.2021*	27.12.2021	29.12.2021
4	06.01.2022	08.01.2022	10.01.2022
5	14.01.2022	16.01.2022	18.01.2022
6	21.01.2022	23.01.2022	25.01.2022
7	26.01.2022	28.01.2022	30.02.2022
8	04.02.2022	06.02.2022	08.02.2022
9	11.02.2022	13.02.2022	15.02.2022
10	18.02.2022	20.02.2022	22.02.2022
11	25.02.2022	27.02.2022	01.03.2022
12	04.03.2022*	05.03.2022	07.03.2022
13	11.03.2022	13.03.2022	15.03.2022
14	18.03.2022	20.03.2022	22.03.2022
15	01.04.2022	03.04.2022	05.04.2022
16	08.04.2022	10.04.2022	12.04.2022
17	14.04.2022	16.04.2022	18.04.2022
18	22.04.2022	24.04.2022	26.04.2022
19	28.04.2022	30.04.2022	02.05.2022
20	06.05.2022	08.05.2022	10.05.2022

* Due to logistical constraints, this session was performed only 24h before/after match (instead of 48h).

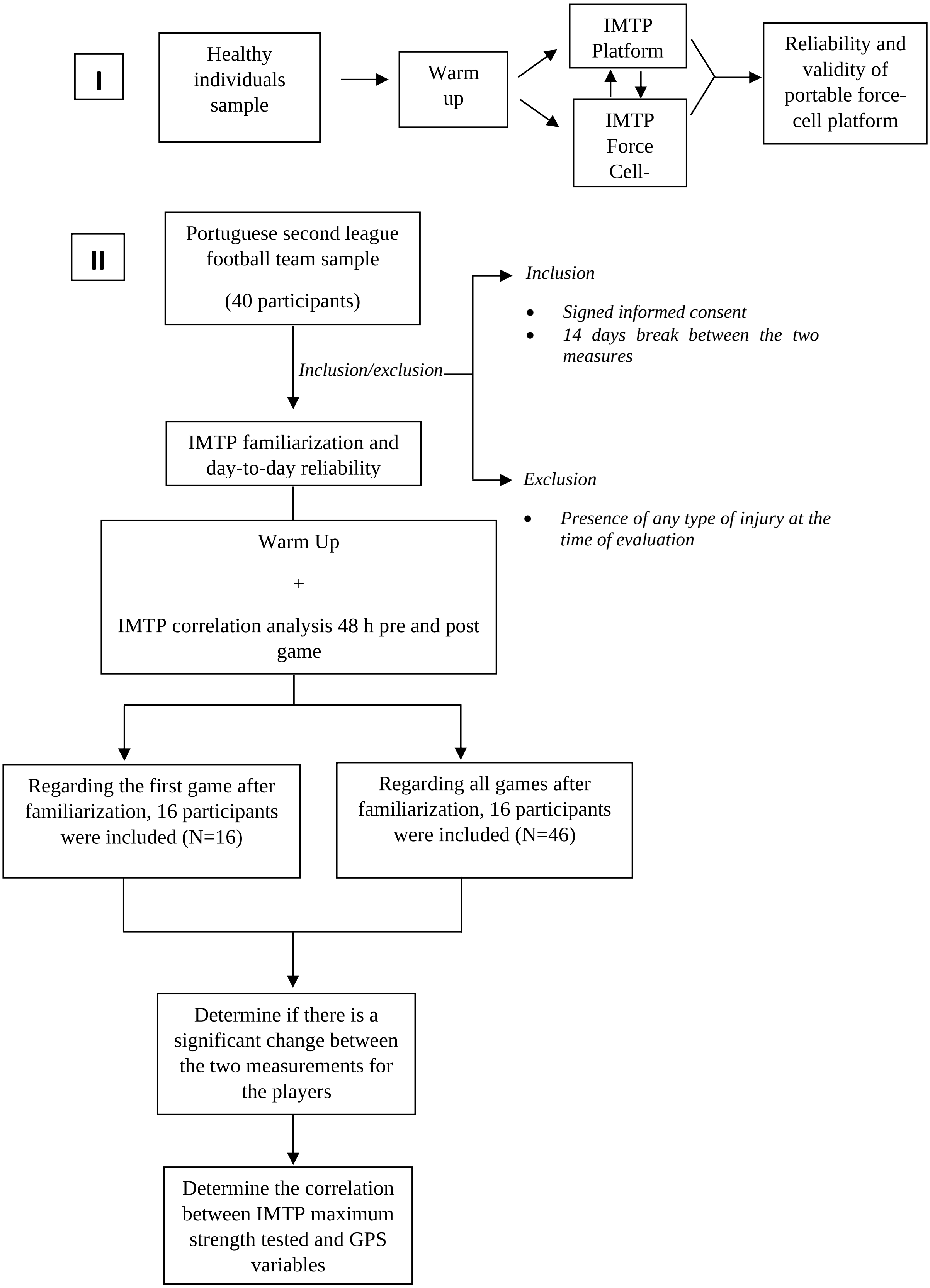

Figure 5. *Study design i) experimental I; ii) experimental II*

3.2 Participants

For this purpose, healthy active men (age: 21.9 ± 3.3 years, height: 171.6 ± 5.74 cm, body mass: 71.7 ± 7.45 kg) were recruited to perform one testing session. After these preliminary tests, footballers were individually selected for participation in the study (age: 24.9 ± 4.8 years, height: 180,6 ± 7,50 cm, body mass: 76,3 ± 6,93 kg). Before the start of the study, participants were informed about the research project purpose and characteristics, including individual participant's responsibilities, rights, and procedures of the study. A signed consent form was required from each athlete who agreed to participate. The sample size permitted use of GPower 3.1 software for determining significant differences using one-way repeated analysis of variance, considering an effect size of 0.3, significance level of $p < 0.05$, statistical power of 0.8. Correlation analysis was by a bivariate normal model test, considering an effect size of 0.4, significance level $p < 0.05$, statistical power of 0.8, for two samples. This was performed for a first session after familiarization and then for all sessions after familiarization, in which participants took IMTP measurements before and after games. Athletes presenting any type of neuromuscular or orthopedic injury were excluded from participating in this study.

3.3 IMTP test Apparatus

Isometric mid-thigh pull force platform

For objective 1, the stationary force platform, located in the university was used. This platform has force sensors at floor level, inside a rack (Figure 6A). The loads that are applied on the platforms are converted into electrical voltages through the sensitivity matrix of each platform. These voltages are then amplified and converted through an analog/digital (A/D) converter. These digital signals are visualized by the operator *via* computer, and can be adjusted to normalize the signal in relation to the body mass of each evaluated individual. It was possible to adjust the bar to a height equivalent to that displayed on the portable force-cell platform (Figure 6B). (APPENDIX I). These adjustments allowed customization of the test set-up to individual participant's specifications, so the lift could begin from mid-thigh level.

Isometric mid-thigh pull portable force-cell platform

Maximum peak force exerted during the isometric mid-thigh pull test was monitored using a customized readily portable apparatus, where an S-Type Load Cell Sensor (Model: LT-LJ-S; Max capacities: 500Kg; Output impedance: 350 ± 3ohm; Insulation resistance: More than 2000 megohm; Input impedance: 365 ± 5 ohm; Weight: 638g; 24-bit and 80Hz; Chronojump, Boscosystem) was connected to the lift- handle/bar of the apparatus used to perform the test (Figure 6). The IMTP testing apparatus was designed so as to allow adjustment of the height of the handle in relation to the foot support platform. These adjustments permitted customization of the test set-up to individual participant's specifications, so the lift could begin from mid-thigh level. A sensor was connected to a perforated shaft (every two cm) that passed through a tube connected to the support platform. In this manner, testing was conducted according to any adjustments in the height of the handle. The force was recorded using an AC/DC converter from Chronojump and analyzed using the Chronojump software (Chronojump 2.1.2-2; Chronojump Networks).

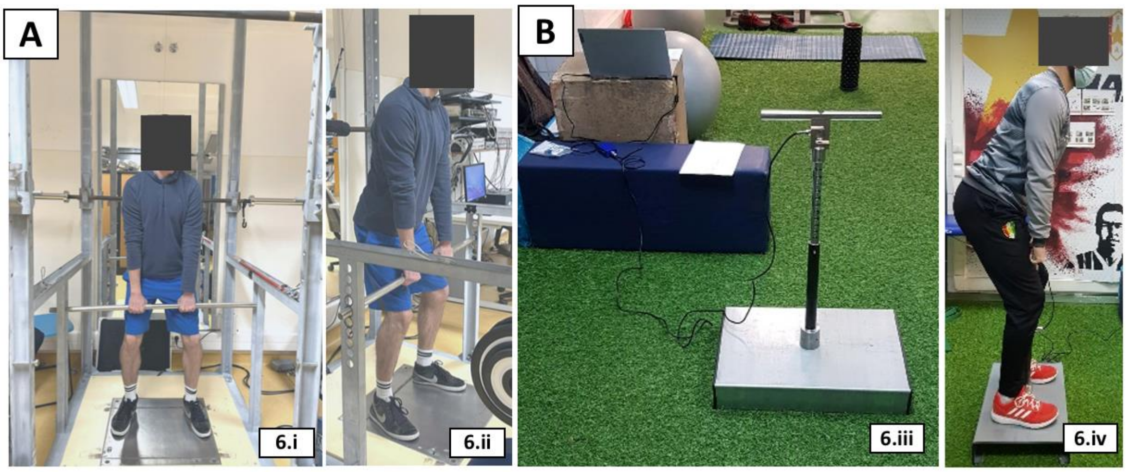

Figure 6*. A) Force platform frontal (6i) and side (6ii) views; B) Isometric mid-thigh pull (IMTP) equipment and testing position: (6iii) Photo of the IMTP testing apparatus showing the standing force-cell platform, the adjustable pull-handle and position of the sensor connected to the data recording computer. (6iv) Lateral view of test subject showing position for initiating test on the IMTP apparatus.*

External loading parameters during football matches

A wearable global position tracking system (GPS; gpexe, It model, 18 Hz GPS speed & position tracking; Excelio, Udine, Italy) was used to track distance-related movements on the field and time played of each athlete during matches. Acceleration and deceleration were monitored when above 2.5 m/s^2, total distance covered and interval distances were monitored at the following zone velocities: zone 1 (Vel_1) (< 16 Km/h), zone 2 (Vel_2) (16 km/h to 19.8 km/h), zone 3 (Vel_33) (19.8 km/h to 25.1 km/h) and zone 4 (Vel_4) (> 25.1 km/h). The on-field distance-metrics, provided by the GPS tracking system, was monitored in relation to the rate of perceived exertion (RPE) of the tracked individual. This information enabled monitoring the training-load of athletes at each session and match [64]. Moreover, GPS was a valid and reliable tool for tracking the external training load, helping to reduce risk of injury and to optimize athletes' physical performances [65]. The gpexe tracker was enclosed in an elastic, corset-like strap and positioned in the center of the upper back between the shoulder blades of participating athletes.

3.4 Protocol

All IMTP test sessions (for healthy individuals and footballers) consisted of a preliminary warm-up period followed by an isometric mid-thigh pull task. At the start of each testing session, athletes completed an ~two-minute standardized warm-up protocol consisting of 20 reverse lunges, 20 jumping jacks, 10 squats and 10 hip thrusts. IMTP tests consisted of performing three attempts of maximum vertical force, using the handgrip located close to mid-thigh, with a slight flexion of the knees (~140º between thigh and calf) and hips (~135º between thigh and torso)[11]. The upper body was maintained with the back straight and, in a position where participants felt comfortable at pulling with as much force as possible (maximal strength/ peak force). The height to which the handle was pulled was recorded at the first testing session and served as a benchmark reference point for further sessions. Participants were instructed to take a starting position of arms extended (no bending of the elbows, see Figure 6), and then pulling the handle bar for ~three seconds with as much force as possible (peak force). Performance feedback was provided to the participant after each attempt. A minimal rest period of one-minute was given between attempts. Peak force of each trial was recorded and used for further analysis.

Each athlete performed, in a phase of familiarization with the equipment/test, three sessions with three attempts, in order to verify if there was a learning-effect in use of the equipment.

Athletes performed the test with the intention of reaching a maximum effort in each repetition. According to the literature [66]. Verbal instruction in this study was always the same, "perform as hard and as fast as possible", so the athletes achieved the best possible performance in the IMPT test. Participants were instructed to "get ready" and then were given a countdown of "3, 2, 1, GO!" Verbal encouragement was provided during each trial. The hand position was shoulder-width apart, using the most convenient and comfortable type of grip. Also, the most comfortable height of the bar within the mid-thigh area was determined. Bar height was recorded for each athlete, so that it was standardized, and maintained at that height for each session.

3.7 Data extraction

The highest peak force achieved and the mean peak force in the IMTP trials of each session was used for further statistical analysis, and for calculating the neuromuscular fatigue coefficient after each match (*i.e.*, percentage of difference between IMTP force values recorded two days pre-match *versus* two days post-match).

3.8 Statistical Analysis

All statistical analyses were carried out using IBM SPSS Statistics software (v28.0. IBM Corp, Armonk, NY, USA). Data were tested for normality and homogeneity of variance using the Shapiro-Wilk and Levene's tests, respectively. For each study objective, the following tests were conducted:

Objective 1: first, to test the validity of the portable platform, we performed the paired samples t-test in order to see if there were differences between the platforms, that is, if they would measure different values.

Objective 2: to examine the effect of familiarizing participants to the IMTP test, peak force data from the first four pre-match testing sessions were analyzed using one-way repeated measures ANOVA. Day-to-day reliability between the second and third and third and fourth pre-match testing sessions was determined by calculating the coefficient of variation (CV), intraclass correlation coefficient (ICC) and the standard error of measurement (SEM) [67].

Objective 3: in order to understand whether the portable platform would measure different forces or not, 48h before and after the game day, the Wilcoxon test was performed, to determine if there had been changes in peak force.

Lastly, to test objective 4, we did Pearson's and Spearman correlation analyses and linear regression to understand if some correlations between external load from the game day (through GPS variables) and loss/change of peak force absolute, PRE and POS, existed, predicting any levels of fatigue, through IMTP testing. Correlations between variables where data were normally distributed, Pearson's correlation coefficient was calculated, and where not normally distributed, Spearman's correlation coefficient was calculated.

Statistical significance was set at $p < 0.05$. The magnitudes of both Spearman's and Pearson's coefficients were classified as weak (< 0.3), moderate (0.3-0.7) and strong (>0.7) [68], appendix 4.1 and 4.2). Correlations between the external game load variables (amount of time played, level of sprinting, distances covered, *etc.*) and percentage of change of strength (peak force) in the IMTP measurement, including all sessions before and after games (excluding the first two familiarization sessions) were analyzed.

CHAPTHER IV: Results

4.1 Concurrent validity of IMPT measurements

To test hypothesis 1, healthy individuals were chosen: Data were found to be normally distributed for both IMTP tests ($p>0.05$). Paired sample t-test was used to understand IMTP measurements on the force platform [1693.9±112.5 newtons (N)] were significantly lower ($p<0.001$) than IMTP measurements on the portable force-cell platform [1880.3±156.5 N;]. Low concurrent validity was observed between these two platform tests [intra-class correlation (ICC) = 0.47 (95% CI = -0.21- 0.79); CV = 10.8% (95% CI = 6.88 – 14.8%)].

Thus, it appears results of IMTP tests between the two types of test platforms are not interchangeable and are not correlated ($p>0.05$) (Figure 7). Data from the two tests cannot be combined in an analysis of the effects of variables on IMTP scores.

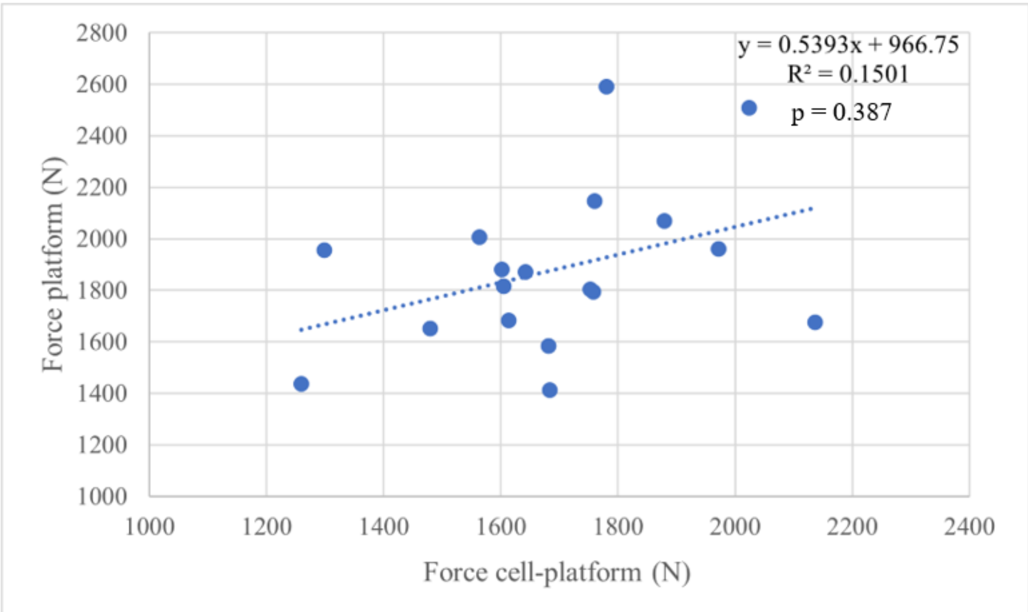

Figure 7. *Scatter plot and linear regression of IMTP peak forces (newtons, N) between the Force platform and Force cell-platform.*

4.2 Participants compliance

The data used for the analysis of IMTP tests in footballers were collected over an 18-week period. Participation of players in performing test protocols was also recorded. Forty players were available for testing, but many did not fully participate. Prior to the pull for the IMPT test, participants had the bar positioned at 78 ± 2.5% leg length (mean = 91.9 ± 5.9 cm; range = 84-110 cm). A total of 16, of the 40 players who volunteered for this study, were assessed for the relationship of external load and its effects on changes in strength, pre- vs. post-game (not including the familiarization measurements). For the entire study, a total of 16 and 46 IMTP pre- and post-game individual sessions were made with these players, excluding familiarization, for two samples (first game and all games after familiarization, respectively). Among all players and all sessions, a total of 4320 IMPT tests (2160, each, before and after games, usually required two to three test pulls per player) were conducted. Of these, a total of 250 test sessions were performed before games, as not all players participated at any particular session. The mean participation in pre-game tests was 6.3±4.1 sessions per player, approximately 12% of the total, involving a total of 665 tests/attempts [mean 16.6±11.0 tests/attempts per player; per cent coefficient of variability (%CV) = 66%]. There was a decline in the participation in post-game sessions as the study progressed. Post-game test sessions totaled 191 IMPT evaluations (mean 4.8±3.4 sessions per player; %CV = 72%), approximately 9% of the total, involving 514 tests/attempts (mean 12.9± 9.2 testing attempts per player). This information is shown in *APPENDIX II*. There was a slightly higher rate of drop-out by participants in post-game tests (mean participation pre-game = 44.7±13.48%; vs. mean participation post-game = 40.5± 13.57%) (appendix 2.1).

4.3 IMTP testing learning-effect and inter-session reliability

To test hypothesis 2, the familiarization period with the IMTP test consisted of pre-game sessions prior to the first four games, separated by a maximum of 11.7±3.0 days between sessions. Players who had only two familiarization sessions or had an interval of days greater than 14 days were excluded from analysis. The Shapiro-Wilk normality test showed data (measurements of force in newtons, N) from the four familiarization sessions were normally distributed (1st session = 0.955, P = 0.514; 2nd session = 0.931, P = 0.199; 3rd session = 0.948, P = 0.399; 4th session = 0.969, P = 0.771). ANOVA for repeated measures, without Greenhouse-Geisser correction, plus multiple Bonferroni Corrections showed significant differences between all early sessions (Session 1 vs. 2 = 37.4, $p < 0.002$; Session 1 vs. 3 = 45.184, $p < 0.001$; Session 1 vs. 4 = 51.8, $p < 0.001$), indicating there was a process of familiarization among the players between the first session and those that followed. However, between latter sessions (those after session one) there were no significant differences between sessions with good reliability [69] (Session 2 vs. 3 = 49.6, p = 0.085; Session 3 vs. 4 = 58.9, p = 1.000; (ICC = 0.842 and ICC = 0.838, respectively; SEM = 176.7 N). Hence, it appeared after the 2nd session, athletes had become familiarized with the mechanics and physical positioning for the test (Figure 8).

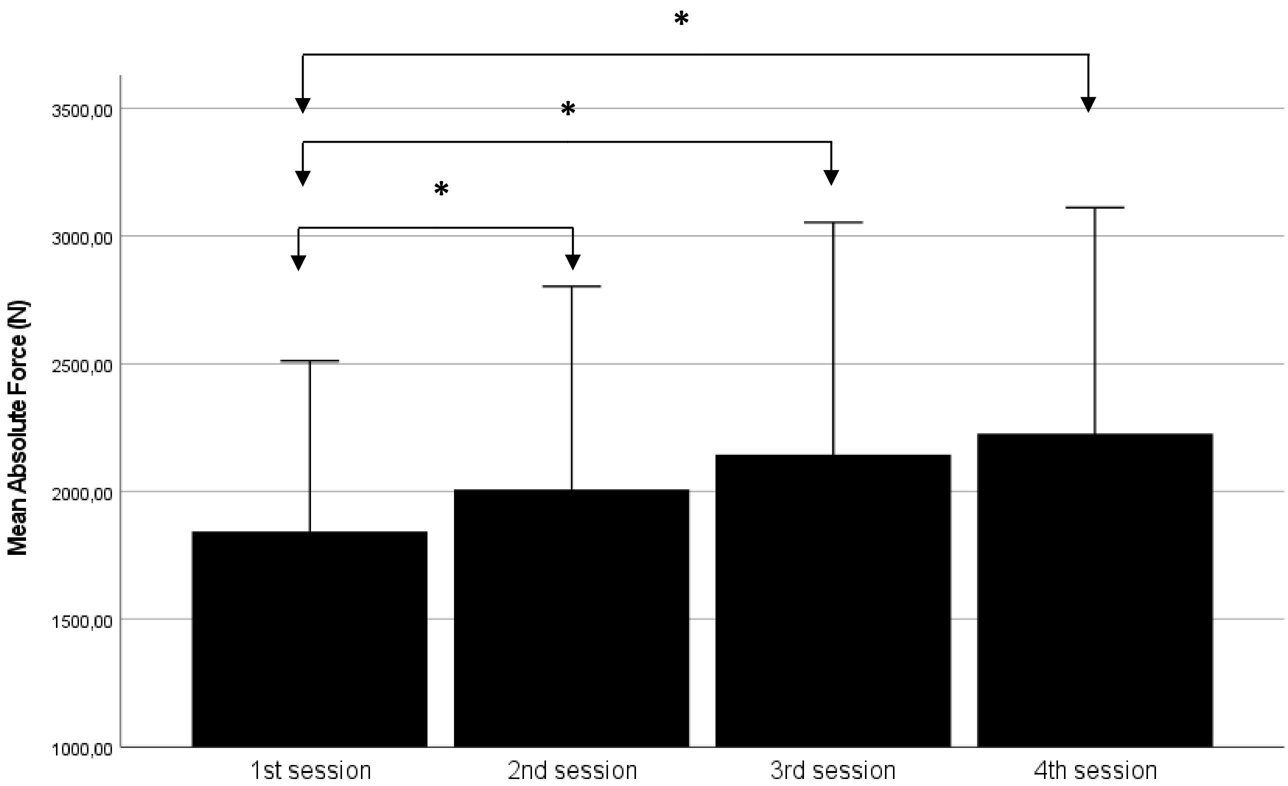

Figure 8. *Mean peak force (newtons, N) mearurements for first four familiarization sessions prior to the first four games; * The average difference is significant at the 0.05 level.*

4.4 Effects of a football match on IMTP peak force

For testing hypothesis 3, a preliminary examination of changes in a player's IMPT maximum peak force was examined after the first test session (third game) (pre- vs post-game IMPT, N). This relationship between external load imposed by game-play and loss/change in strength in IMTP measurements, before and after game-play, excluding the familiarization sessions (the first two games), is illustrated in Figure 9. Of the 16 players tested and who participated, seven showed a loss of force between pre- and post-game tests, eight showed a gain of force and one showed no change. The Shapiro-Wilk normality test did not show normal distribution for pre- vs post-game IMTP (N) (W = 0.750, P < 0.001). Wilcoxon test showed this difference was not statistically significant (Z = -0.362, P = 0.744).

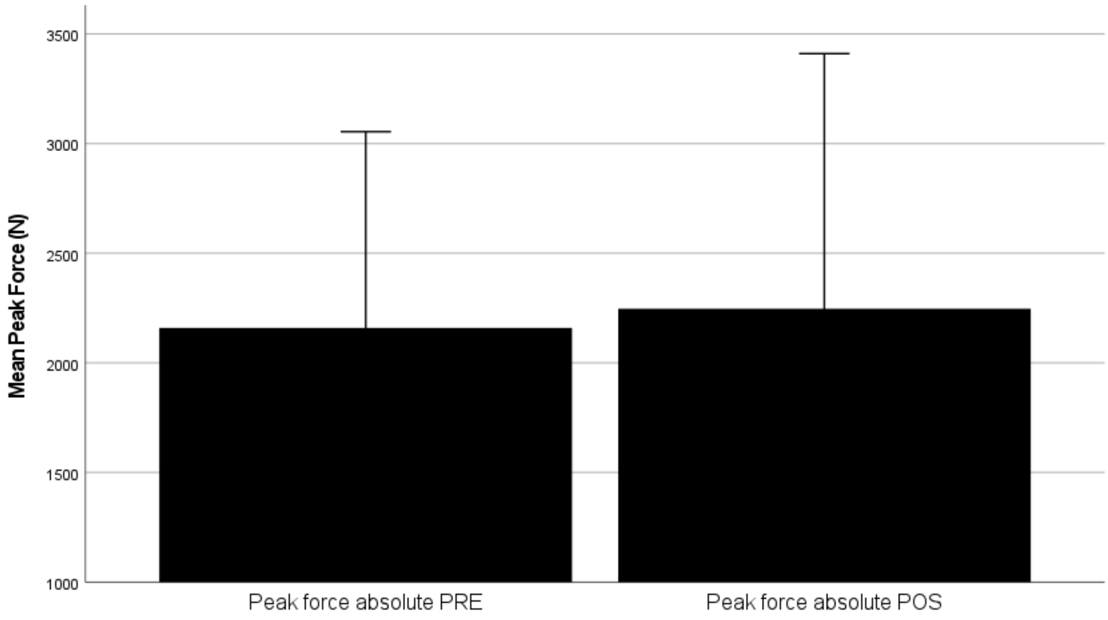

Figure 9. *General comparison of PRE and POS game peak strength values (newtons, N), relative to the first session after familiarization (3rd test session) (n = 16)*

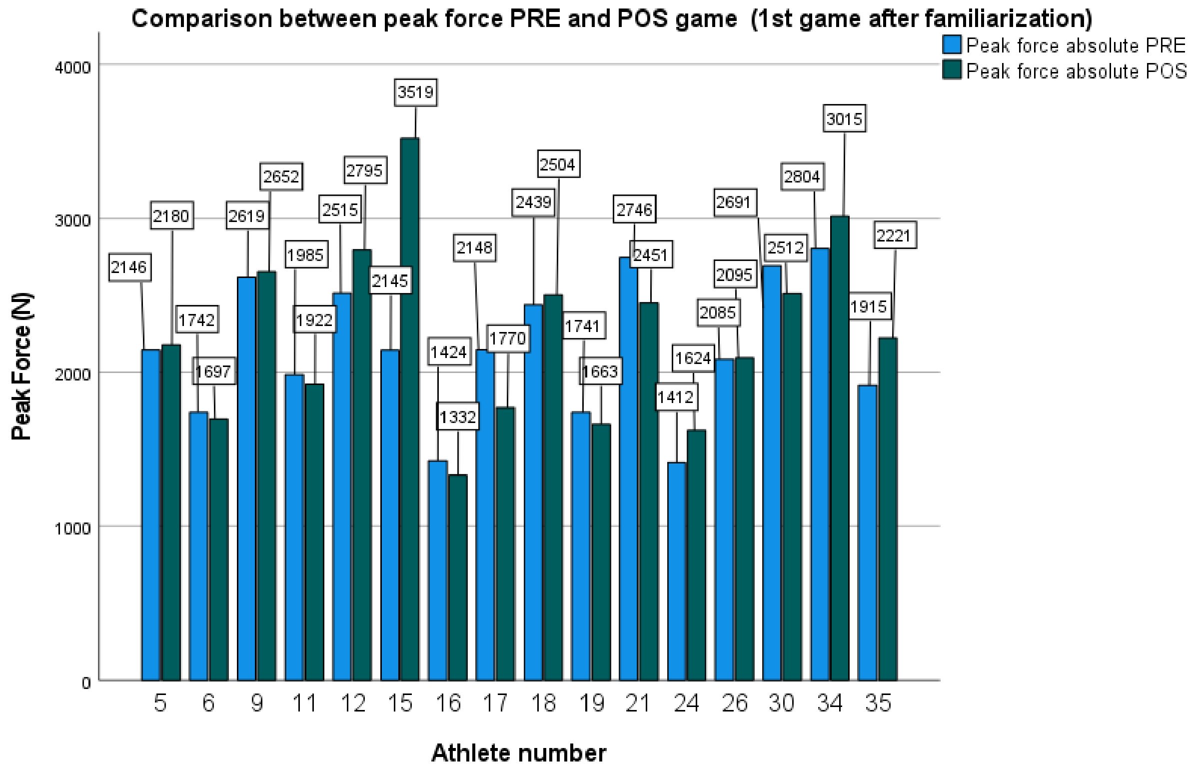

Figure 10. *Strength values (newtons, N) of individual athletes obtained before (PRE) and after (POS) the first test game (third session; first session, after first two familiarization sessions).*

This relationship between the external load imposed by game-play and the change in strength (N) based on IMTP measurements, before and after game-play, is shown in Figure 10. Of the 16 players who participated in all these sessions, six showed a loss of force, seven a gain and one no change. The Shapiro-Wilk normality test did not show normal distribution for pre- vs post-game IMTP (N) (W = 0.934, P = 0.016). Wilcoxon test showed this difference was not statistically significant (Z = -0.652, P = 0.520).

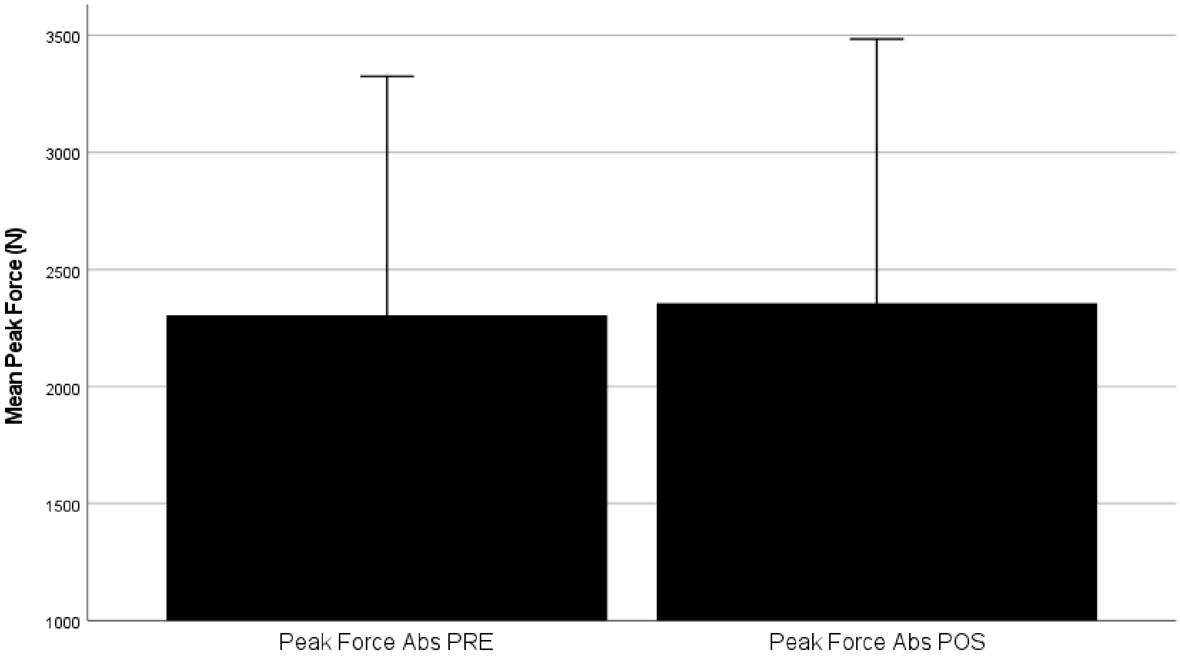

***Figure 11**. General comparison of PRE and POS game mean peak strength values (newtons, N), relative to all games after familiarization (n = 46)*

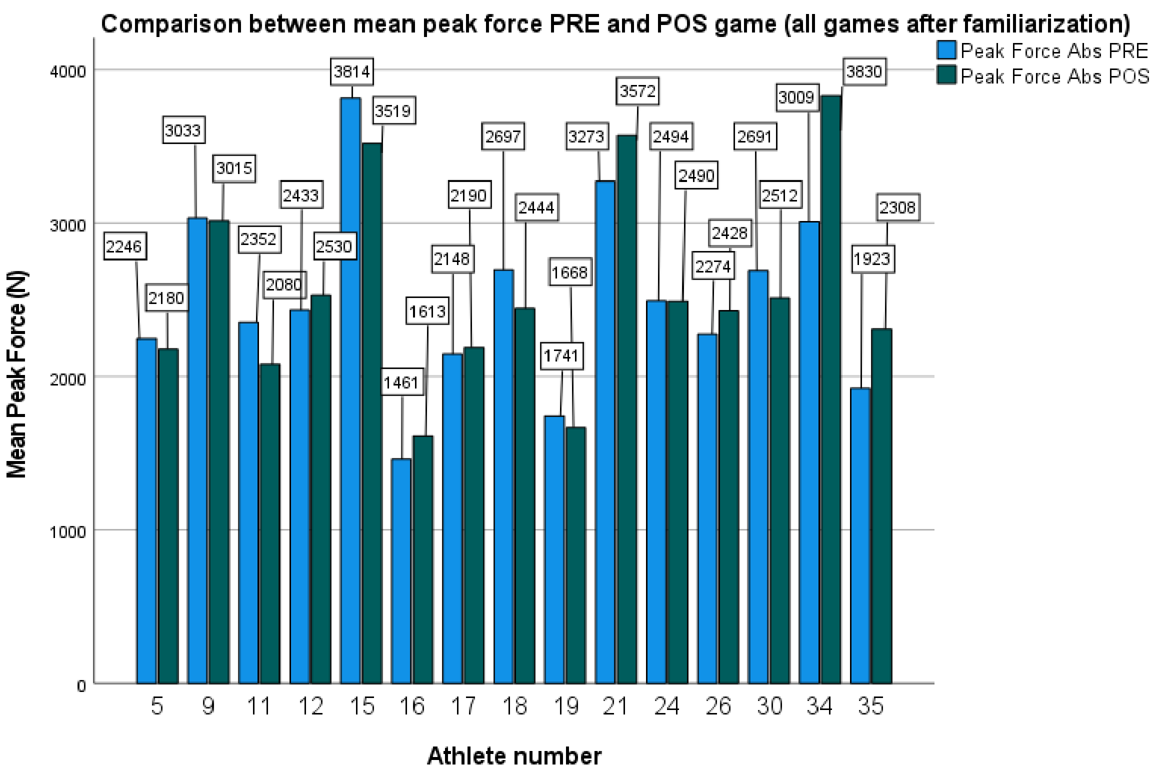

Figure 12*. Histograms showing mean level of maximum peak force (newtons, N), measured by IMPT, of individual players before (PRE) and after (POS) play, for all test sessions (all sessions after the two familiarization sessions).*

In direct comparison between an individual player's trend in pre- and post-game changes in force between the third game, after familiarization, (Figure 11) and the remaining total games (Figure 12), out of 32 comparisons, 18 players showed the same trends in pre- vs post- game changes in force. Six showed a trend of gain in force post-game and ten showed a trend of loss of force, post-game. Hence, a majority of players showed no change in trends in IMTP testing from the third to all remaining sessions.

4.5 Correlation analyses between IMTP performance before and after matches and the external loading outcomes during official football matches

4.5.1 *Relationship between external load and Peak force Abs PRE and POS (all games after familiarization)*

For testing Objective 4, normality of data was verified, using the Shapiro-Wilk normality test ($p>0.05$), for variables relating to absolute peak force before the game (Peak force absolute PRE) (P = 0.512), distance covered in Distance_Vel_2 (Distance_Z2) (P = 0.158), number of accelerations performed (Accelerations) (P = 0.178) and game density (Time played/Total distance) (P = 0.181).

Pearson's correlation coefficients were calculated between the variables. There was one moderate and statistically significant ($p<0.05$) correlation (Figure 13). A significant negative correlation included "Peak Force absolute PRE (N)" vs "Accelerations" (r = -0.501; P = 0.048) (appendix 5.2). Strikingly, there were no clear correlations between Peak Force Changes, between pre- and post-game tests and any of the variables. Moreover, there were no visible correlations among the remaining variables (appendix 5.2).

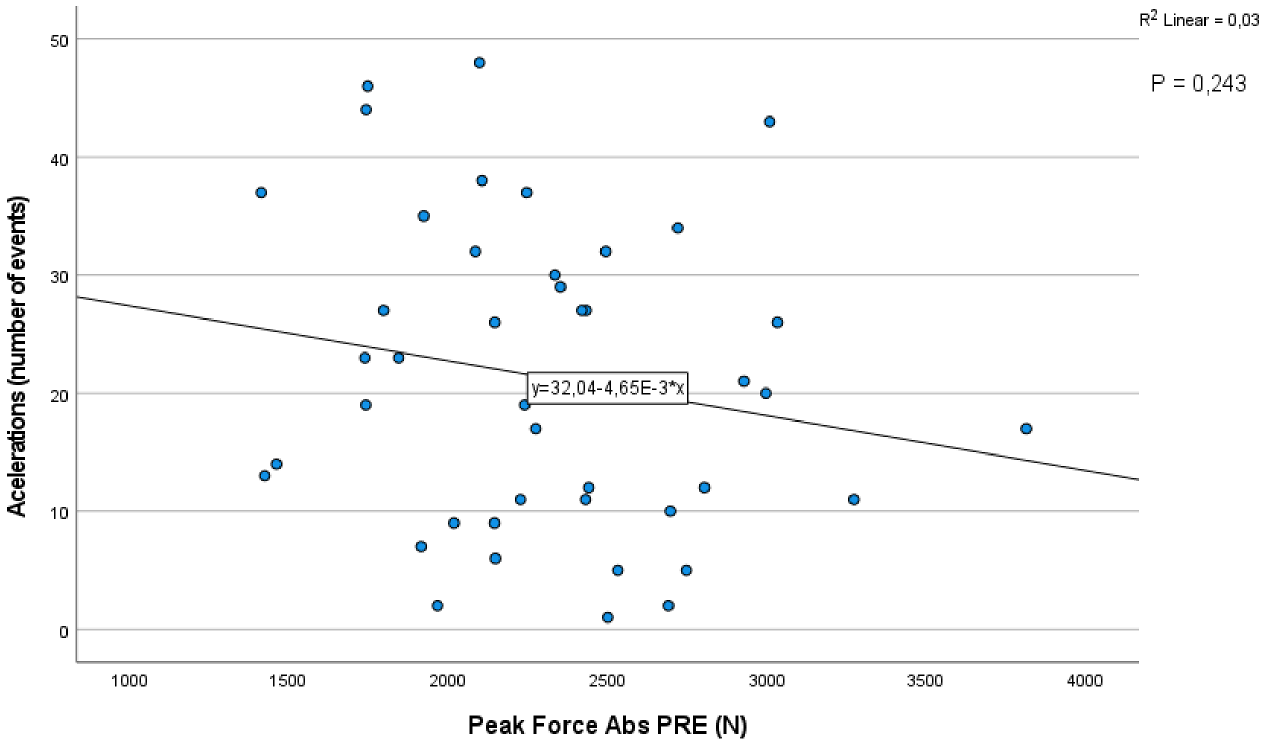

***Figure 13**. Linear regression between Peak Force Abs PRE (N) and Accelerations (number of events) made during game play (y= 32,04-4,65E-3^x)*

There were moderate, but not statistically significant, correlations between Peak Force Abs POS and following variables: a positive correlation with percentage of force loss from pre- and post-game measurement (Peak force loss) (POS/PRE-1) (r= 0.421; p=0.105); negative correlation with total distance covered (Total distance) (r= -0.447 and p= 0.083); negative correlations with distance covered including Z1 (Distance_Vel_1) (r= -0.397 and p=0.128), Z3 (Distance_Vel_3 (r= -0.382 and p= 0.144) and Vel_4 (Distance_Vel_4) (r= -0.218 and p= 0.418); a negative correlation with number of decelerations performed (Decelerations) (r= -0.355 and p= 0.177); and a negative correlation with game time played (Time played) (r= -0.281 and p=0.292). There were no statistically significant correlations between Peak Force Loss (appendix 5.2) and other variables represented among the data that were not normally distributed.

4.5.2 *Relationship between external load and changes in Peak force Abs PRE and POS (1st game after familiarization)*

Data for the third session (third game) were tested for normality using the Shapiro-Wilk normality test. Data were found to be normally distributed with the exception for variables of Peak force loss, Total Distance, Distance_Vel_1 and Vel_4 and Time played. Of the normally distributed data, Pearson's correlation coefficient was calculated. Several significant correlations (p<0.05) were found. These included a significant positive correlation between Peak force absolute PRE and Peak force absolute POS (r= 0.738

and p<0.001) (Figure 14) and a moderate negative correlation between Peak force absolute Pre with Accelerations (r= -0.501 and p= 0.048) (Figure 15).

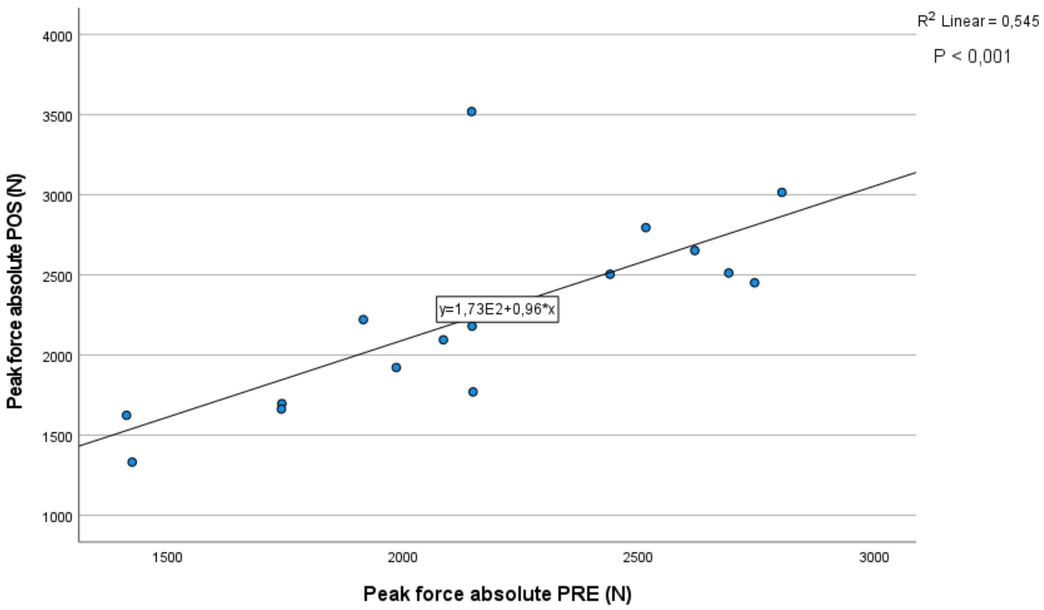

Figure 14*. Linear regression between Peak force absolute POS and Peak absolute force PRE (newtons, N).*

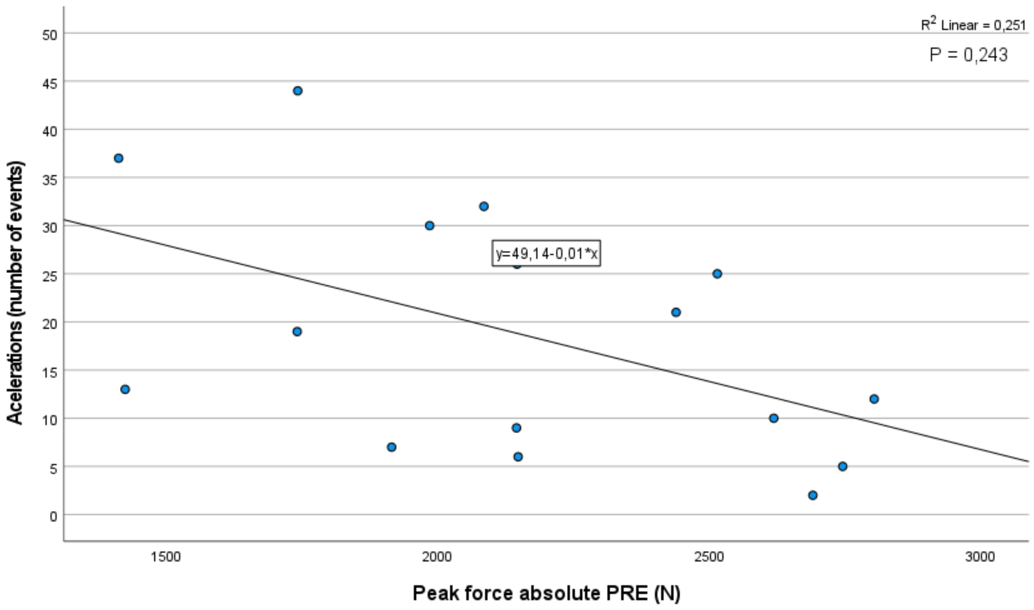

Figure 15*. Linear regression between Accelerations (number of events) and Peak absolute force PRE (newtons, N).*

Visibly moderate negative correlations, but not statistically significant, were also observed between PRE and Distance Z2 (r= -0.446 and p = 0.083), Distance Z3 (r= -0.390 and p= 0.135), and Decelerations (r= -0.385 and p= 0.141). Significant positive correlations were found between Distance Z2 and the following variables: Distance Z3 (r= 0.825 and p<0.001), Accelerations (r= 0.825 and p<0.001) and Decelerations (r= 0.850 and p<0.001). Significant positive correlations were found between Distance Z3 and the following variables: Accelerations (r= 0.899 and p<0.001) and Decelerations (r= 0.883 and p<0.001). A significant positive correlation was found between Accelerations and Decelerations (r= 0.939 and p<0.001). It appeared that Time Played/Total Distance did not have any significant or visible correlations with any of the other variables (appendix 5.1).

With respect to Peak force absolute POS some moderate negative correlations were found with the following variables: Distance Z2 (r= -0.469 and p = 0.067), Distance Z3 (r= -0.398 and p= 0.127), Accelerations (r= -0.402 and p= 0.123), Decelerations (r= -0.323 and p= 0.223) and a weak positive correlation with Time Played/Total Distance (min/m) (r= 0.109 and p= 0.687) (appendix 5.1).

For non-normally distributed data measured during the third session (fourth game) Spearman's correlation was used to discern any correlations among these variables. Within this set of cases, strong positive correlations were found between Total Distance with Distance_Vel_1 (r= 0.991 and p< 0.001) and with Time Played (r= 0.955 and p< 0.001) and between Distance_Vel_1 and Time Played (r= 0.967 and p< 0.001) (appendix 5.1). Apart from these correlations, Peak force loss (%) showed weak and non-significant correlations (appendix 5.1). Collectively, the positive correlations regarding distances run, time-played, and accelerations/decelerations made by GPS tracking, indicated the gpex devices were reliable tools for assessing player activity levels.

CHAPTHER V: Discussion

This study, to the best of our knowledge, is one of the first to use the IMTP to assess neuromuscular fatigue in professional football players, though having already been applied to young players [9]. Goalkeepers were excluded from the analyses in view their positions involve a significant reduction in activity and distance covered compared to the other players. As such, their GPS data would undoubtedly be outliers and not applicable to this study. The main findings were:

5.1 Concurrent validity of the IMPT testing

Hypothesis 1) the two isometric mid-thigh pull test systems did not show concurrent validity [ICC = 0.47 (95% CI = -0.21- 0.79), CV = 10.8% (95% CI = 6.88 – 14.8%)]. This could be due to the sensor in the force platform being underneath the feet during the test. Whereas, the sensor on the portable force cell platform was near the hands (in addition to the possibility of changes to the testing position). This position may have allowed a dispersion or use of forces, which may or may not favor the athlete, as had already been observed by other authors [41].

Despite absence of significant correlations relating to muscle fatigue in this study, as was verified in the literature, that IMTP test is relevant to evaluate the performance of professional soccer players, providing information on which methodologic training direction to follow with the player [40].

5.2 Familiarization and inter-session reliability

Hypothesis 2) there was an increase in the peak of maximum force during the first three weeks during the familiarization period (mean force: 1st session = 1843 N; 2nd session = 2008 N; 3rd session = 2143.6 N). Also, only two sessions were required for the familiarization process for the IMTP test to occur, with notable reliability values (ICC = 0.842). This requirement for familiarization was also verified in the literature. Our results concur with that of the literature proving IMTP to be a consistent and reproducible test [10]. Some authors have demonstrated that a minimum of four familiarization sessions are required [42], while others cite at least two familiarization sessions are necessary [10][43]. We found the results of this study were in agreement with the literature, that familiarization sessions are required. However, our results found only two sessions are needed.

5.3 Effects of football match on IMTP performance

Hypothesis 3) There were no statistically significant differences in maximum force two days prior to (PRE) and two day after (POST) a match, according to our study design, neither during the familiarization period (Z = -0.362, P = 0.744) nor for all games after familiarization (Z = -0.652, P = 0.520). Even though these were the results presented, we were able to observe some interesting trends, as follows: of all players, six players lost force, pre- *versus* post- game, and seven players actually gained force, and two showed no change. This indicated, based on our study design, nine of the 16 players assessed did not show loss of force 48h post-game, excluding the familiarization games. Out of 32 comparisons of pre- *versus* post-game changes in force, 18 players showed the same trends from those measured in the singular third game (Figure 9) and the mean for all the remaining games (Figure 10) in pre- *versus* post force, four showed a trend of gain in force post-game and two showed a trend of loss of force, post-game. One reason for this variability can be due to player-motivation for performing the test. On the day before pre-game testing, the team had the most intense training of the week (-3 game day) and even some players reported back pain and/or grip pain, prior to the pre-game test. Moreover, every position on the pitch may require different demands of effort. Hence, a majority of players showed no change in trends in IMTP testing from the third game to all remaining sessions. Interestingly, the data indicates that in most cases 48h post-game players had already recovered from any game-related fatigue and, in some cases, had actually increased their strength and performance by 48h post-game. This observation has already been reported by some authors [46]. Another possibility is that measuring force 48h post-game is too long a period to assess muscle fatigue using IMTP, as muscle fatigue may have recovered, by then.

5.4 Relationship between IMPT peak force and footballers external loading during official matches

Hypothesis 4) In analyzing all games following those involved with familiarization (peak force pre- and post- game) some moderate correlations and a few strong correlations between variables were found. Firstly, "Accelerations", according to the literature, represent 7-10%, for total player load of all positions [55]. This variable is to be taken into account, as it reflects changes that occur before and after the game, at the biochemical and neuromuscular level [52]. This trend was also verified in this thesis, as number of accelerations had moderate to significant negative correlations ($r = -0.501$ and $p=0.048$) with "Peak force absolute PRE", a good indicator of neuromuscular fatigue after the game (higher number of accelerations during the match resulted in loss of peak force after the match). Secondly, the first game after familiarization, showed a positive, strong, and significant correlation between Peak force absolute PRE with POS ($r = 0.738$ and $p<0.001$). This could simply indicate that stronger players, according to IMTP measurements, before the match, maintained their strength and remained stronger after the match. Hence, these players exhibited lower muscle strain than the weaker athletes, as has been reported previously [13]. Among correlations of variables of Distance Z2, Distance Z3, Total distance, Decelerations, in both datasets analyzed (first game and all games after familiarization), with Peak force absolute PRE and POS (appendix 5.1 and 5.2), some were found to be negative, moderate and non-significant, but indicating some trend of predicting fatigue/changes after games (less strength/peak force).

5.5 LIMITATIONS

The location of the load cell, on portable force-cell platform used in our study was close to the hands instead of being under the feet, might be an issue with regard to being able to compare force data between the platforms. Also, this thesis had what might be considered to having a small sample size. Many players complained of back and/or grip pain during the IMTP tests, which could have affected participation. Taking IMTP measurements two days before an upcoming match may not be the best period to make such tests, especially as the -3DJ training was most intense just the day before these pre-match measurements. There is the possibility there was already residual muscle fatigue the day after this practice, when the pre-match IMTP tests were made. Also, making post-match force assessments by IMTP 48h after the match may not be optimal to assess muscle fatigue, as significant muscle recovery may have already taken place. These factors in the timing of taking the IMTP tests should be taken into consideration for future studies. Optimal, of course, would be to make post-match IMTP measurements directly following the match. But, it may be difficult to solicit players to cooperate with testing at that time as they are tired. Also, to make accurate post-match assessments directly after the match, may require the owner of the team and/or the coach demand player cooperatation. Lastly, somewhat of an issue was player cooperation, in general., On average, many players were not always motivated to take the test, especially following the period of familiarization.

CHAPTHER VI: Conclusion

Our study found significant differences between the types of equipment used to assess IMTP. Given that the application of forces on the portable (force-cell) dynamometer is performed close to the hands and, on the force platform, close to the feet, additional studies will be needed to examine the relevance of tests using these different platforms for having a common purpose but generating different outcomes.

Some interesting trends were found between IMTP peak force absolute PRE and POS game and player external load, as assessed by GPS, showing force measurements in some cases correlated with player fatigue relative to amount of game load. With this information, an individual player's training program can be adjusted accordingly. The ability to customize a player's force/strength/resistance training could enable faster recovery and improved performance, overall, especially for the next, upcoming game.

The IMTP test has been [6] [10][11] and was found in our research to be a safe and reliable measure of maximal strength. It provides relevant performance indicators and is a recommended test to monitor, evaluate and predict professional football players' physical performance and post-match recovery. The results of IMTP tests provide valuable data to assist in directing any type of intervention, that might be indicated, for use by strength and conditioning coaches [40]. However, further research and additional studies to examine relevance of these types of test, in the world of football are indicated.

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ATTACHEMENTS

APPENDIX I

1.1 Table of biometric data of pilot test subjects, to validate the portable platform; Experimental I (Objective 1)

Nº	Weight	Height	Date of birth	Test date	Age	Altura_IMTP		
						Force cell	Force platform	Weight(N)
1	89,7	182	22/04/1997	07/02/2022	24,8	72	73	880
2	68,5	177	23/11/2000	07/02/2022	21,2	70	69	672
3	69,1	176	03/09/2000	07/02/2022	21,4	70	69	678
4	65,5	170	23/11/2000	07/02/2022	21,2	68	69	643
5	70,9	170	17/11/2000	07/02/2022	21,2	66	65	696
6	79,3	183	16/06/2002	07/02/2022	19,6	72	73	778
7	64,5	170	06/11/2002	07/02/2022	19,3	68	69	633
8	69,0	168	05/04/1998	18/02/2022	23,9	66	65	681
9	68,0	166	05/06/2002	19/02/2022	19,7	68	69	690
10	77,0	173	25/01/2000	20/02/2022	22,1	70	69	768
11	63,5	160	30/09/1999	03/02/2022	22,3	62	61	623
12	69,7	166	16/07/2002	03/02/2022	19,5	66	65	684
13	74,1	170	09/04/2002	03/02/2022	19,8	68	69	727
14	63,3	169	27/11/1994	03/02/2022	27,2	66	65	621
15	85,0	176	23/05/2002	03/02/2022	19,7	68	69	834
16	63,6	173	02/06/2002	03/02/2022	19,7	68	69	624
17	74,7	167	05/10/2002	03/02/2022	19,3	64	65	733
18	74,3	173	02/12/1989	03/02/2022	32,2	68	69	729

A_IMTP_Platform			B_IMTP_Cell			Tests order		Platform	Cell	Platform	Cell	Dif %	Dif	%CV
R1	R2	R3	R1	R2	R3			abs	abs	rel	rel	8,36%		
2564	2685	2759	2069	1976	2038	A	B	1879	2069	20,9	23,1	9,20%	-190,37	6,82%
1971	1866	1962	1955	1938	1646	B	A	1299	1955	19,0	28,5	33,57%	-656,45	28,53%
2262	2248	2283	1816	1789	1786	A	B	1605	1816	23,2	26,3	11,62%	-210,97	8,72%
2193	2308	2423	2169	2512	2590	B	A	1780	2590	27,2	39,5	31,28%	-810,18	26,22%
2298	2229	2208	1688	1675	1880	A	B	1602	1880	22,6	26,5	14,79%	-278,00	11,29%
2750	2744	2684	1927	1859	1961	B	A	1972	1961	24,9	24,7	-0,56%	11,00	0,40%
2109	2178	2196	2006	1974	1885	A	B	1563	2006	24,2	31,1	22,08%	-443,00	17,55%
2636	2600	2705	2344	2508	2390	B	A	2024	2508	29,3	36,3	19,30%	-484,00	15,10%
2055	2051	2372	1476	1560	1585	A	B	1682	1585	24,7	23,3	-6,12%	97,00	4,20%
2528	2501	2381	2146	1940	2124	B	A	1760	2146	22,9	27,9	17,99%	-386,00	13,98%
2175	2262	2265	1854	1870	1783	A	B	1642	1870	25,9	29,4	12,19%	-228,00	9,18%
2010	2163	2088	1546	1652	1575	B	A	1479	1652	21,2	23,7	10,47%	-173,00	7,81%
2863	2774	2625	1546	1676	1672	A	B	2136	1676	28,8	22,6	-27,45%	460,00	17,07%
2235	2043	2025	1579	1684	1628	B	A	1614	1684	25,5	26,6	4,16%	-70,00	3,00%
2518	2488	2385	1412	1409	1367	A	B	1684	1412	19,8	16,6	-19,26%	272,00	12,42%
1883	1753	1820	1437	1324	1304	B	A	1259	1437	19,8	22,6	12,39%	-178,00	9,34%
2447	2312	2491	1369	1773	1795	A	B	1758	1795	23,5	24,0	2,06%	-37,00	1,47%
2474	2482	2380	1803	1759	1632	B	A	1753	1803	23,6	24,3	2,77%	-50,00	1,99%

APPENDIX II

2.1 Overall attendance record of athletes tested

	N					DATES		
Week	PRE	POST	N total	% n Pre	% n Post	PRE	Game	POST
1	20	17	27	74,1%	63,0%	12/12/2021	13/12/2021	15/12/2021
2	20	18	27	74,1%	66,7%	17/12/2021	19/12/2021	21/12/2021
3	16	15	27	59,3%	55,6%	26/12/2021	27/12/2021	29/12/2021
4	19	9	30	63,3%	30,0%	08/01/2022	09/01/2022	12/01/2022
5	12	8	32	37,5%	25,0%	22/01/2022	23/01/2022	25/01/2022
6	13		31	41,9%		26/01/2022	28/01/2022	
7	13	13	31	41,9%	41,9%	06/02/2022	08/02/2022	10/02/2022
8	13	13	32	40,6%	40,6%	13/02/2022	14/02/2022	16/02/2022
9	10	12	32	31,3%	37,5%	19/02/2022	21/02/2022	23/02/2022
10	12	10	32	37,5%	31,3%	25/02/2022	27/02/2022	02/03/2022
11	14	7	35	40,0%	20,0%	04/03/2022	05/03/2022	07/03/2022
12	15	16	35	42,9%	45,7%	10/03/2022	12/03/2022	15/03/2022
13	11	12	34	32,4%	35,3%	18/03/2022	20/03/2022	23/03/2022
14	14		34	41,2%		01/04/2022	03/04/2022	
15	12	10	34	35,3%	29,4%	14/04/2022	16/04/2022	19/04/2022
16	14	17	34	41,2%	50,0%	21/04/2022	23/04/2022	25/04/2022
17	13	12	34	38,2%	35,3%	28/04/2022	30/04/2022	03/05/2022
18	11		34	32,4%		06/05/2022	08/05/2022	
			Average	44,72%	40,48%			
			SD	13,48%	13,57%			

2.2 Attendance record of individual athletes tested

	Nº Pre-Games tests																			
Nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Nº tests	total sessions
1	3	3	2	3	3	3	3	3	2		2								27	10
2	3	3													2				8	3
3		3																	3	1
4																			0	0
5	3	3	1		3		3	2	2										17	7
6	3	3	3	3															12	4
7	3	3																	6	2
8						1													1	1
9	3	3	2	3	3		3		3										20	7
10	3																		3	1
11	3	3	2	3		3										2			16	6
12	3	3	3	3	3	3	3		3			2							26	9
13	3	3	3																9	3
14			3	3	3	3		2		2	2		3	2			2	2	27	11
15	3	3		1			3	2	2	1		2		2	2	1			22	11
16	3	3	3	3	3					1				3					19	7
17	3	3	2	3															11	4
18					3	3	3	3		2	3	3	3	3	2	2	3		33	12
19	3	3	3	3	3		3	3				2							23	8
20	3	3	3																9	3
21	3	3	3	3	3	3	3	3			2	2							28	10
22	3	3	3	3															12	4
23						3	1												4	2
24	3	3	3	3	3		3	2	3	3	3	3		3	2	3			40	14
25	3	3																	6	2

	Nº Pre-Games tests																			
Nº	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	Nº tests	total sessions
26		3	3	3													2		11	4
27																			0	0
28				3						3	3	3	2	3		2	2	2	23	9
29				3		3				3	3	3	2	3	3	2	2	2	29	11
30				3		3				3	3	3	2	3		2	2	2	26	10
31											3	3	2	3	3	2	2	2	20	8
32				3															3	1
33				3		3	3	3	2	3	2	2	2		3	2	2	2	32	13
34					3	3	3	3	3	3		3	2	3	3	2	2	3	36	13
35						3		3	3	3	3	3	2	3	3	2	3	2	33	12
36					3			3	1							2			9	4
37								3		3									6	2
38											3	3		3	3	3	2	3	20	7
39											3	3	2	3	3		2	2	18	7
40											3		2	3	3	2	2	2	17	7
	19	20	16	19	12	13	12	13	10	12	14	15	11	14	12	14	13	11		
	57	60	42	55	36	37	34	35	24	30	38	40	24	40	32	29	28	24	665	250
	3	3	2,6	2,9	3,0	2,8	2,8	2,7	2,4	2,5	2,7	2,7	2,2	2,9	2,7	2,1	2,2	2,2	16,6	6,3
	0	0	0,6	0,5	0,0	0,6	0,6	0,5	0,7	0,8	0,5	0,5	0,4	0,4	0,5	0,5	0,4	0,4	11,0	4,1
	0%	0%	24%	16%	0%	19%	20%	18%	29%	32%	17%	18%	19%	13%	18%	23%	17%	19%	66%	66%

Followed meausures

14 days break between the two measures

Nº	Nº Post-Games tests																		Nº tests	total sessions	total
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18			
1	3	3	3				3	2											14	5	0
2	3			3															6	2	0
3		3																	3	1	0
4																			0	0	0
5	3	3	3		1			2	1			1							14	7	0
6	3	3	3																9	3	0
7																			0	0	0
8			3																3	1	0
9	3	3	3	3			3												15	5	0
10																			0	0	0
11		3	3							3					2	3			14	5	0
12	3	3	3	3	3		3		2										20	7	0
13	3	3	3																9	3	0
14		3	3	3	3		3	3	2	2	3		2			3	2		32	12	0
15	3	3		3			2			2	2	2				2			19	8	0
16	3	3	3	3							2	3				2			19	7	0
17	3	3	3	3							1								13	5	0
18				3			3	3	3	3		3				3	3		24	8	0
19	3	3	3									2	2						13	5	0
20	3	3																	6	2	0
21	3	3	3		3		3				2								17	6	0
22	3	3	3																9	3	0
23																			0	0	0
24	3	3	3	3			3	2	2	3	3	3	3				1		32	12	0
25	3															2			5	2	0

Nº	Nº Post-Games tests																		Nº tests	total sessions	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18			
26	3	3	3													2	2		13	5	
27																			0	0	
28								3	3			3	2		2	2	2		17	7	
29							3	3	3	3		3	3		3	2	2		25	9	
30							3	3	3	3		3	3		2	2	2		24	9	
31												2	3		2	2	2		11	5	
32																			0	0	
33					3		3	3	2	3		2			3	3			22	8	
34					3		3	3	3	3	3	3	2		2	3	2		30	11	
35					3		3	3	3	3		3	3			2	2		25	9	
36					3			3											6	2	
37								3	3										6	2	
38												3	3		3	2	2		13	5	
39												3	3		3	2	2		13	5	
40												3	3		3	2	2		13	5	
	17	18	16	9	8	0	13	13	12	10	7	16	12	0	10	17	13	0			
	51	54	48	27	22	0	38	36	30	28	16	42	32	0	25	39	26	0	514	191	
	3,0	3,0	3,0	3,0	2,8	#DIV/0	2,9	2,8	2,5	2,8	2,3	2,6	2,7	#DIV/0	2,5	2,3	2,0	#DIV/0	12,9	4,8	
	0,0	0,0	0,0	0,0	0,7	#DIV/0	0,3	0,4	0,7	0,4	0,8	0,6	0,5	#DIV/0	0,5	0,5	0,4	#DIV/0	9,2	3,4	
	0%	0%	0%	0%	26%	#DIV/0	9%	16%	27%	15%	33%	24%	18%	#DIV/0	21%	20%	20%	#DIV/0	72%	72%	#

APPENDIX III

3.1 Athletes’ data table for familiarization; Experimental 2 (objective 2)

	Sessions Date				Days between sessions			Absolute Maximum Force (N)				%CV				Relative Maximum Force (N / Kg)				S3-S4
	1ª	2ª	3ª	4ª	1-2	2-3	3-4	1ª	2ª	3ª	4ª	1-2	2-3	3-4	1-4	1ª	2ª	3ª	4ª	
Nº	Date	Date	Date	Date				Max	Max	Max	Max					Rel	Rel	Rel	Rel	Dif
1	12/12/2021	17/12/2021	26/12/2021	08/01/2022	5	9	13	1597	1843	2018	2098	10%	6%	3%	12%	20,48	23,33	25,87	26,9	-80
6	12/12/2021	17/12/2021	26/12/2021	08/01/2022	5	9	13	1509	1409	1742	1521	5%	15%	10%	9%	23,22	21,58	26,88	22,98	221
9	12/12/2021	17/12/2021	26/12/2021	08/01/2022	5	9	13	2247	2413	2619	2471	5%	6%	4%	6%	26,13	27,73	30,45	28,73	148
11	12/12/2021	17/12/2021	26/12/2021	08/01/2022	5	9	13	1687	1875	1984	2056	7%	4%	3%	8%	18,96	21,19	22,3	23,63	-72
12	12/12/2021	17/12/2021	26/12/2021	08/01/2022	5	9	13	1959	2014	2229	2514	2%	7%	8%	12%	23,16	23,95	26,04	29,26	-285
14	26/12/2021	08/01/2022	22/01/2022	26/01/2022	13	14	4	2264	2501	2503	2650	7%	0%	4%	6%	28,66	31,66	31,68	33,89	-147
16	12/12/2021	17/12/2021	26/12/2021	08/01/2022	5	9	13	1223	1187	1424	1461	2%	13%	2%	10%	17,98	17,48	20,97	21,33	-37
17	12/12/2021	17/12/2021	26/12/2021	08/01/2022	5	9	13	1792	1825	2148	1966	1%	11%	6%	8%	25,06	25,7	30,04	27,49	182
18	22/01/2022	26/01/2022	06/02/2022	13/02/2022	4	11	7	2018	2403	2439	2697	12%	1%	7%	12%	27,83	33,37	33,88	37,46	-258
19	12/12/2021	17/12/2021	26/12/2021	08/01/2022	5	9	13	1642	1577	1741	1679	3%	7%	3%	4%	21,9	21,03	23,15	22,09	62
21	12/12/2021	17/12/2021	26/12/2021	08/01/2022	5	9	13	2312	2401	2746	2863	3%	9%	3%	10%	26,39	27,6	31,57	33,3	-117
22	12/12/2021	17/12/2021	26/12/2021	08/01/2022	5	9	13	1620	2139	2035	2254	20%	4%	7%	14%	23,14	30,56	28,87	32,43	-219
24	12/12/2021	17/12/2021	26/12/2021	08/01/2022	5	9	13	1368	1525	1412	1797	8%	5%	17%	13%	19,82	22,76	20,77	26,42	-385
28	25/02/2022	04/03/2022	10/03/2022	18/03/2022	7	6	8	2335	2491	2829	2533	5%	9%	8%	8%	31,13	32,95	37,72	33,77	296
31	04/03/2022	10/03/2022	18/03/2022	01/04/2022	6	8	14	1919	2072	1788	2410	5%	10%	21%	13%	23,4	25,27	22,07	29,94	-622
34	22/01/2022	26/01/2022	06/02/2022	13/02/2022	4	11	7	2152	2431	2804	2950	9%	10%	4%	14%	25,95	29,29	33,78	35,54	-146
39	04/03/2022	10/03/2022	18/03/2022	01/04/2022	6	8	14	1637	1976	1724	2053	13%	10%	12%	11%	23,97	29,06	25,35	30,19	-329
40	04/03/2022	18/03/2022	01/04/2022	14/04/2022	14	14	13	1903	2063	2399	2112	6%	11%	9%	10%	29,5	31,5	36,91	33	287
Average					6,1	9,5	11,7	1843,6	2008,1	2143,6	2226,9	6,8%	7,7%	7,2%	10,0%	24,3	26,4	28,2	29,4	
SD					2,8	1,9	3,0	333,7	397,4	454,8	442,2	4,7%	4,0%	5,2%	2,7%	3,7	4,7	5,4	4,8	249,8
																		group	SEM	176,7
																		indv.	MDC	346,3

APPENDIX IV

4.1 Data from PRE and POS game peak strength values, relative to the first session after familiarization (3rd test session) (Objective 3 and 4)

	Dates			Peak force IMPT						Distance				
				Abs			Rel							
Nº	PRE	Game	POST	PRE	POST	%CV	PRE	POS	% loss	Total Distance (m)	Z1 (m) < 16 Km/h	Z2 (m) 16-19,8 Km/h	Z3 (m) 19,8-25,1 Km/h	Z4 (m) > 25,1 Km/h
5	26/12/2021	27/12/2021	29/12/2021	2146	2180	1%	30,22	30,7	1,58%	6656,1	5441,1	584,9	459,2	171
6	26/12/2021	27/12/2021	29/12/2021	1742	1697	2%	26,88	25,87	-2,58%	10303	8342,3	1208,2	600,2	152,3
9	26/12/2021	27/12/2021	29/12/2021	2619	2652	1%	30,45	30,84	1,26%	8881,2	7994,6	561,9	280	44,7
11	26/12/2021	27/12/2021	29/12/2021	1985	1922	2%	22,3	21,6	-3,17%	9709,7	8220,4	807,8	538,2	143,4
12	08/01/2022	09/01/2022	12/01/2022	2515	2795	7%	29,26	32,88	11,13%	9611,4	8234	802,1	465,5	109,8
15	08/01/2022	09/01/2022	12/01/2022	2145	3519	34%	27,86	45,7	64,06%	3377,6	2969,4	246,9	160,7	0,8
16	26/12/2021	27/12/2021	29/12/2021	1424	1332	5%	20,97	19,73	-6,46%	8368,7	7411,1	668,7	222,7	66,1
17	26/12/2021	27/12/2021	29/12/2021	2148	1770	14%	30,04	24,76	-17,60%	3413,3	2600,2	445,1	339,2	28,8
18	06/02/2022	08/02/2022	10/02/2022	2439	2504	2%	33,88	34,78	2,67%	7897,6	6543,6	914,4	370,5	69,2
19	26/12/2021	27/12/2021	29/12/2021	1741	1663	3%	23,15	22,08	-4,48%	8186,4	7196,6	700,8	240,7	48,3
21	26/12/2021	27/12/2021	29/12/2021	2746	2451	8%	31,57	28,51	-10,74%	2387,9	1928,1	247,4	155,9	56,5
24	26/12/2021	27/12/2021	29/12/2021	1412	1624	10%	20,77	24,24	15,01%	10110,5	8755	645,2	536,9	173,4
26	26/12/2021	27/12/2021	29/12/2021	2085	2095	0%	25,43	25,54	0,48%	8878,2	7753,6	720,6	366,4	37,7
30	21/04/2022	23/04/2022	25/04/2022	2691	2512	5%	30,58	28,55	-6,65%	865,1	665,4	34	88,8	771
34	06/02/2022	08/02/2022	10/02/2022	2804	3015	5%	33,78	36,77	7,52%	2425,9	1964	202,4	200,7	58,9
35	18/03/2022	20/03/2022	23/01/2022	1915	2221	10%	28,16	32,66	15,98%	1601	1199,1	193,8	143,2	65

	External load							Game played (minutes)	Game density (m/min)
		Events							
Nº	Z4 (m) > 25,1 Km/h	Accelerations (> 2,5 m/s2)	Decelerations (> 2,5 m/s2)	Speed	Met power	Max met power (W/kg)	Avg met power (W/kg)		
5	171	26	51	39	107	93,93	8,82	59	0,89%
6	152,3	44	70	65	168	129,62	8,3	97	0,94%
9	44,7	10	36	25	101	142,9	6,21	97	1,09%
11	143,4	30	42	45	132	95,95	7,34	97	1,00%
12	109,8	25	38	42				99	1,03%
15	0,8	9	18	15	55	101,19	8,19	31	0,92%
16	66,1	13	21	25	48	79,07	7,85	77	0,92%
17	28,8	6	14	22	114	84,16	9,89	27	0,79%
18	69,2	21	38	41	123	87,93	9,74	64	0,81%
19	48,3	19	26	22	114	94,92	7,98	75	0,92%
21	56,5	5	12	15	36	96,08	8,91	20	0,84%
24	173,4	37	49	46	139	110,9	7,77	97	0,96%
26	37,7	32	54	34	147	84,13	6,49	97	1,09%
30	771	2	3	5	11	118,56	9,14	8	0,92%
34	58,9	12	14	15	38	94,89	7,95	23	0,95%
35	65	7	11	13	25	8489	9,03	14	0,87%

4.2 Data from PRE and POS game peak strength values, relative to all the games after familiarization (Objective 3 and 4)

Nº	Game Nº	Dates			Peak force IMPT						External load						
					Abs			Rel			Distance					Events	
		PRE	Game	POST	PRE	POST	%CV	PRE	POST	% loss	Total Distance (m)	Z1 (m) < 16 Km/h	Z2 (m) 16-19,8 Km/h	Z3 (m) 19,8-25,1 Km/h	Z4 (m) > 25,1 Km/h	Accelerations (> 2,5 m/s2)	Decelerations (> 2,5 m/s2)
5	3	26/12/2021	27/12/2021	29/12/2021	2146	2180	1%	30,22	30,7	-1,58%	6656,1	5441,1	584,9	459,2	171	26	51
	4	22/01/2022	23/01/2022	25/01/2022	2246	2051	6%	31,85	29,1	8,68%	11400,2	8956,8	1130,6	919,7	393,2	37	72
6	3	26/12/2021	27/12/2021	29/12/2021	1742	1697	2%	26,88	25,87	2,58%	10303	8342,3	1208,2	600,2	152,3	44	70
9	3	26/12/2021	27/12/2021	29/12/2021	2619	2652	1%	30,45	30,84	-1,26%	8881,2	7994,6	561,9	280	44,7	10	36
	7	06/02/2022	08/02/2022	10/02/2022	3033	3015	0%	34,87	36,64	0,59%	9461,9	8533,9	616	263.5	48,7	26	29
11	3	26/12/2021	27/12/2021	29/12/2021	1985	1922	2%	22,3	21,6	3,17%	9709,7	8220,3	807,8	538,2	143,4	27	33
	4	21/04/2022	23/04/2022	25/04/2022	2352	2080	9%	27,03	23,91	11,56%	9651,7	7947,6	796,2	624,5	283,5	29	42
12	4	08/01/2022	09/01/2022	12/01/2022	2229	2139	3%	26,04	24,96	4,04%	9611,4	8234	802,1	465,5	109,8	25	38
	5	22/01/2022	23/01/2022	25/01/2022	2433	2530	3%	28,65	29,87	-3,98%	9910,5	8621	726,8	422,4	140,5	27	62
	6	06/02/2022	08/02/2022	10/02/2022	2227	1891	12%	26,45	22,27	15,09%	6433,5	5637,4	493,1	254,2	48,9	11	19
	7	19/02/2022	21/02/2022	23/02/2022	2419	2507	3%	28,8	29,85	3,64%	10638,1	8984,7	1130,4	480	43,1	27	62
15	3	08/01/2022	09/01/2022	12/01/2022	2145	3519	34%	27,86	45,7	64,06%	3377,6	2969,4	246,9	160,7	0,8	9	18
	4	06/02/2022	08/02/2022	10/02/2022	3814	3000	17%	50,18	40	-21,34%	4402,5	3692,4	374,6	258,9	76,6	17	22
	5	25/02/2022	27/02/2022	02/03/2022	2928	3105	4%	38,53	40,59	6,05%	5394,9	4239,9	690,1	410,1	54,9	21	42
	6	10/03/2022	12/03/2022	15/03/2022	2997	3352	8%	38,92	43,53	11,85%	3294,1	2653,8	361,5	209	69,8	20	21
16	3	26/12/2021	27/12/2021	29/12/2021	1424	1332	5%	20,97	19,73	-6,46%	8368,7	7411,1	668,7	222,7	66,1	13	21
	4	08/01/2022	09/01/2022	12/01/2022	1461	1613	7%	21,33	23,38	10,40%	7192,6	6447,2	458	223,5	64	14	22
17	3	26/12/2021	27/12/2021	29/12/2021	2148	1770	14%	30,04	24,76	-17,60%	3413,3	2600,2	445,1	339,2	28,8	6	14
	4	08/01/2022	09/01/2022	12/01/2022	1966	2190	8%	27,49	30,64	11,39%	517,2	455,5	46	15,8	0	2	2
18	3	06/02/2022	08/02/2022	10/02/2022	2439	2504	2%	33,88	34,78	2,67%	7897,6	6543,6	914,4	370,5	69,2	21	38
	4	13/02/2022	14/02/2022	16/02/2022	2697	2444	7%	37,36	33,94	-9,38%	1944,7	1472,2	293	141,4	38,3	10	15
	5	25/02/2022	27/02/2022	02/03/2022	2240	2424	6%	31,11	33,67	8,21%	5678,1	4577,2	726,8	331,6	42,4	19	26
	6	10/03/2022	12/03/2022	15/03/2022	2431	2274	5%	33,53	31,37	-6,46%	3633,9	2872,8	472	253,6	35,5	11	18
	7	21/04/2022	23/04/2022	25/04/2022	2532	2312	6%	35,66	32,11	-8,69%	6522,2	5150,2	1057,4	285,2	29,5	5	14
	8	28/04/2022	30/04/2022	03/05/2022	2018	2157	5%	28,22	30,17	6,89%	3009,5	2477,4	365	121,4	45,9	9	10
19	3	26/12/2021	27/12/2021	29/12/2021	1741	1663	3%	23,15	22,08	-4,48%	8186,4	7196,6	700,8	240,7	48,3	19	26
	4	10/03/2022	12/03/2022	15/03/2022	1738	1668	3%	22,57	21,95	-4,03%	11295,4	9072,3	1388,7	750,3	84,5	23	44

N°	Game N°	Speed	Met power	Max met power (W/kg)	Avg met power (W/kg)	Game played (minutes)	Total minutes per player	Game density (min/m)
5	3	39	107	93,93	8,82	59	158	0,89%
	4	71	172	114,56	9,07	99		0,87%
6	3	65	168	129,62	8,3	97	97	0,94%
9	3	25	101	142,9	6,21	97	195	1,04%
	7	29	123	118,77	6,91	98		
11	3	38	109	115,87	6,82	97	193	0,99%
	4	54	118	116,76	7,47	96		
12	4	42				99	356	1,03%
	5	47	156	90,98	8,04	99		1,00%
	6	22	93	147,21	8,21	58		0,90%
	7	47	156	90,98	8,04	100		0,94%
15	3	15	55	10119	8,19	31	130	0,92%
	4	26	59	9108	7,66	28		0,64%
	5	44	99	95,16	10,33	43		0,80%
	6	24	55	879	9,28	28		0,85%
16	3	25	107	79,07	785	77	144	0,92%
	4	19	92	80,24	7,68	67		0,93%
17	3	22	48	84,16	9,89	27	32	0,79%
	4	1	8	69,92	8,94	5		0,97%
18	3	41	123	87,93	9,74	64	225	0,81%
	4	12	25	80,47	10,11	15		0,77%
	5	31	89	92,12	10,31	44		0,77%
	6	23	59	101,98	10,06	29		0,80%
	7	28	106	77,14	10,93	47		0,72%
	8	12	46	156,05	9,03	26		0,86%
19	3	22	114	94,92	7,98	75	175	0,92%
	4	59	171	115,03	8,45	100		0,89%

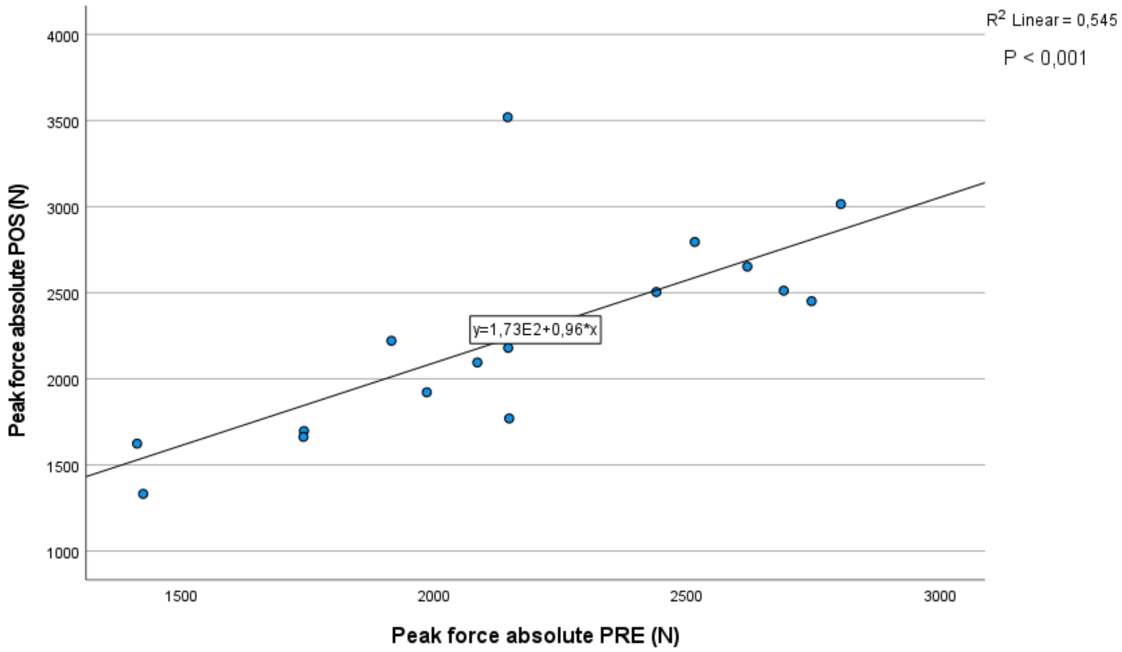
		Dates			Peak force IMPT						External load						
					Abs			Rel			Distance					Events	
Nº	Game Nº	PRE	Game	POST	PRE	POST	%CV	PRE	POST	% loss	Total Distance (m)	Z1 (m) < 16 Km/h	Z2 (m) 16-19,8 Km/h	Z3 (m) 19,8-25,1 Km/h	Z4 (m) > 25,1 Km/h	Accelerations (> 2,5 m/s2)	Decelerations (> 2,5 m/s2)
21	3	26/12/2021	27/12/2021	29/12/2021	2747	2452	8%	31,57	28,51	-10,74%	2387,9	1928,1	247,4	155,9	56,5	5	12
	4	06/02/2022	08/02/2022	10/02/2022	3273	3572	6%	37,67	41,53	9,13%	2874,6	2382,4	229,1	207	56,2	11	17
	5	04/03/2022	05/03/2022	07/03/2022	2720	2200	15%	31,63	25,58	-19,12%	8938,8	7491,2	739,2	548	160,5	34	67
24	3	26/12/2021	27/12/2021	29/12/2021	1413	1624	10%	20,77	24,24	14,93%	10110,5	8755	645,2	536,9	173,4	37	49
	4	08/01/2022	09/01/2022	12/01/2022	1797	2209	15%	26,42	32,48	22,93%	8740,4	7586,8	702,8	339,4	111,4	27	42
	5	06/02/2022	08/02/2022	10/02/2022	2335	2336	0%	34,84	34,87	0,06%	10104,2	8802,8	762,2	415,2	124,1	30	33
	6	13/02/2022	14/02/2022	16/02/2022	1844	2124	10%	27,94	31,42	15,18%	6065,8	5400,8	363	252	50	23	23
	7	19/02/2022	21/02/2022	23/02/2022	2106	1945	6%	31,43	29,03	-7,64%	9488,6	7839,7	956,2	557,4	135,4	38	66
	8	25/02/2022	27/02/2022	02/03/2022	2441	2186	8%	36,98	32,87	-10,45%	4487,3	3788,5	356,1	270,5	72,2	12	20
	9	04/03/2022	05/03/2022	07/03/2022	2098	2028	2%	30,85	29,39	-3,34%	10171,8	8496,9	761,8	673,5	239,7	48	58
	10	10/03/2022	12/03/2022	15/03/2022	2494	2490	0%	36,68	36,62	-0,16%	10671	8713,6	988,5	742,4	226,7	32	67
26	3	26/12/2021	27/12/2021	29/12/2021	2085	2095	0%	25,43	25,54	0,48%	8878,2	7753,6	720,6	366,4	37,7	32	54
	4	28/04/2022	30/04/2022	03/05/2022	2274	2428	5%	28,43	30,35	6,77%	3801,1	3251	371,3	156,2	22,8	17	22
30	3	21/04/2022	23/04/2022	25/04/2022	2691	2512	5%	30,58	28,55	-6,65%	865,1	665,4	34	88,8	771	2	3
34	3	06/02/2022	08/02/2022	10/02/2022	2804	3015	5%	33,78	36,77	7,52%	2425,9	1964	202,4	200,7	58,9	12	14
	4	19/02/2022	21/02/0202	23/02/2022	2500	3003	13%	30,12	36,62	20,12%	1679,2	1109,4	264,1	253,2	52,5	1	3
	5	21/04/2022	23/04/2022	25/04/2022	3009	3830	17%	35,4	45,6	27,28%	10643,1	8506,1	1224,6	766	146,4	43	76
35	3	18/03/2022	20/03/2022	23/01/2022	1915	2221	10%	28,16	32,66	15,98%	1601	1199,1	193,8	143,2	65	7	11
	4	21/04/2022	23/04/2022	25/04/2022	1747	2308	20%	26,07	33,94	32,11%	11049,9	8655,7	1450,6	840	1037	46	59
	5	28/04/2022	30/04/2022	03/05/2022	1923	1960	1%	28,28	28,82	1,92%	10094	8363,5	947,8	627,8	1554	35	39

N°	Game N°	Speed	Met power	Max met power (W/kg)	Avg met power (W/kg)	Game played (minutes)	Total minutes per player	Game density (min/m)
21	3	15	36	96,08	8,91	20	131	0,84%
	4	16	38	110,54	7,15	29		1,01%
	5	56	136	128,14	8,18	82		0,92%
24	3	46	139	110,69	7,77	97	653	0,96%
	4	40	124	97,44	7,24	87		1,00%
	5	43	113	135,58	7,52	99		0,98%
	6	24	122	107,99	8,27	40		0,66%
	7	52	141	98,37	8,19	90		0,95%
	8	24	67	108,59	7,65	44		0,98%
	9	70	151	123,76	8,18	95		0,93%
	10	60	157	95,45	8,03	101		0,95%
26	3	34	147	84,13	6,49	97	139	1,09%
	4	21	54	117,12	6,44	42		1,10%
30	3	5	11	118,56	9,14	8	8	0,92%
34	3	15	38	94,89	7,95	23	132	0,95%
	4	17	25	72,75	11,47	12		0,71%
	5	67	178	113,71	8,51	97		0,91%
35	3	13	25	8489	9,03	14	211	0,87%
	4	87	185	110,58	9,15	97		0,88%
	5	54	156	104,05	7,68	100		0,99%

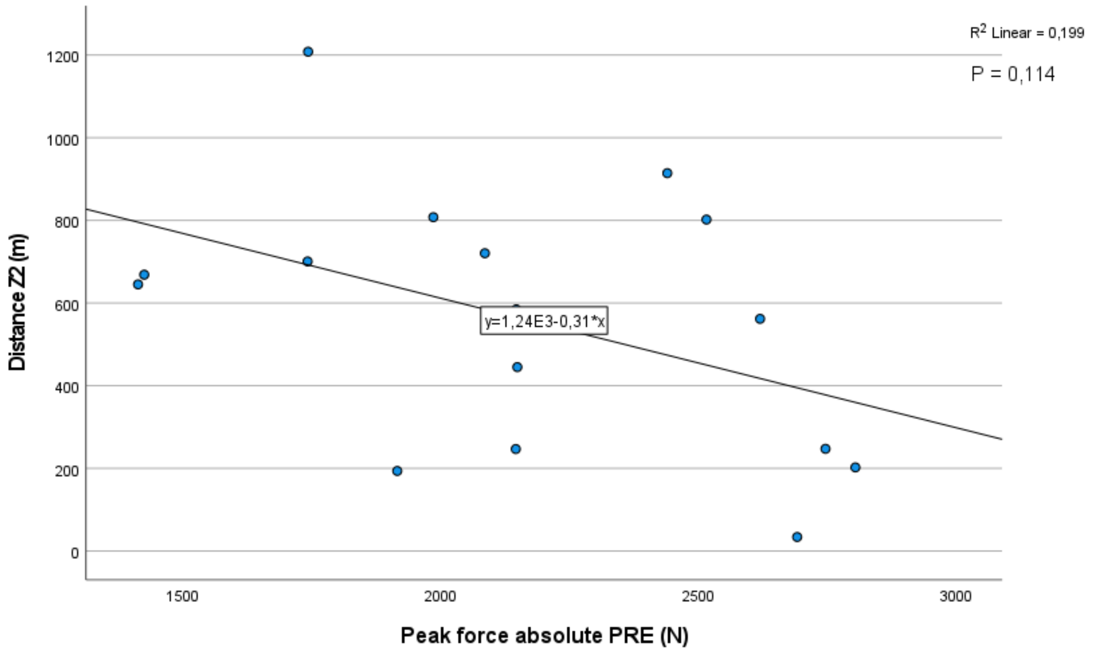
APPENDIX V

5.1 Correlation and regression analyses (1st game after familiarization)

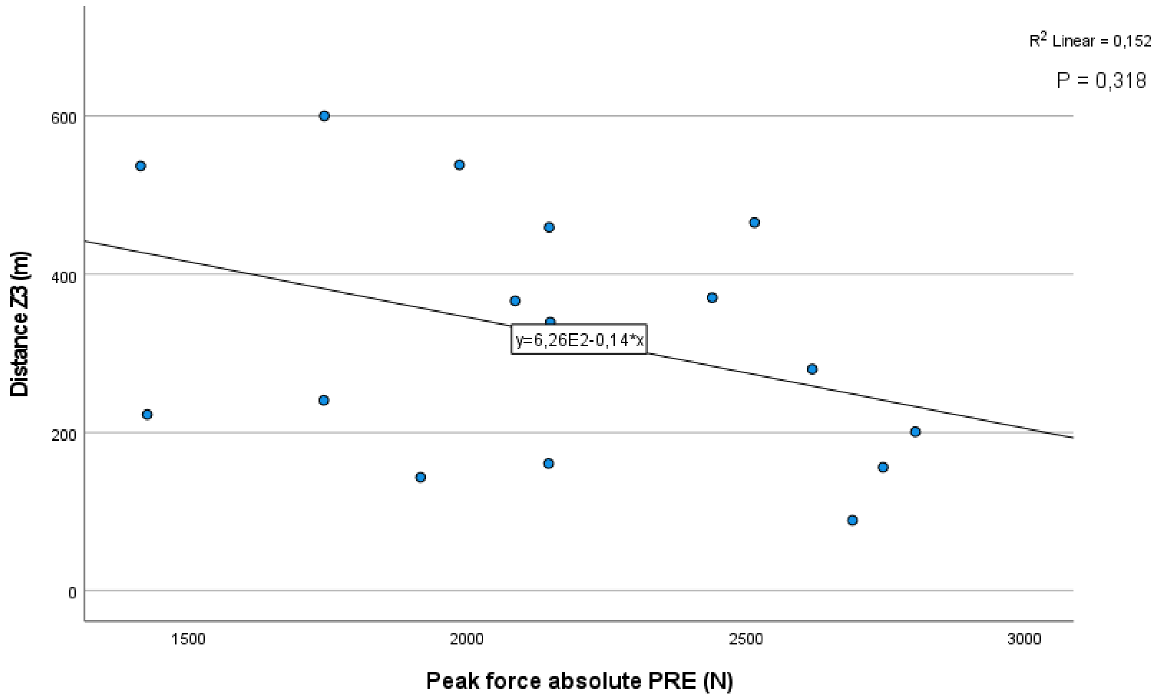
5.1.1 Correlation between Peak force absolute PRE and Peak force absolute POS



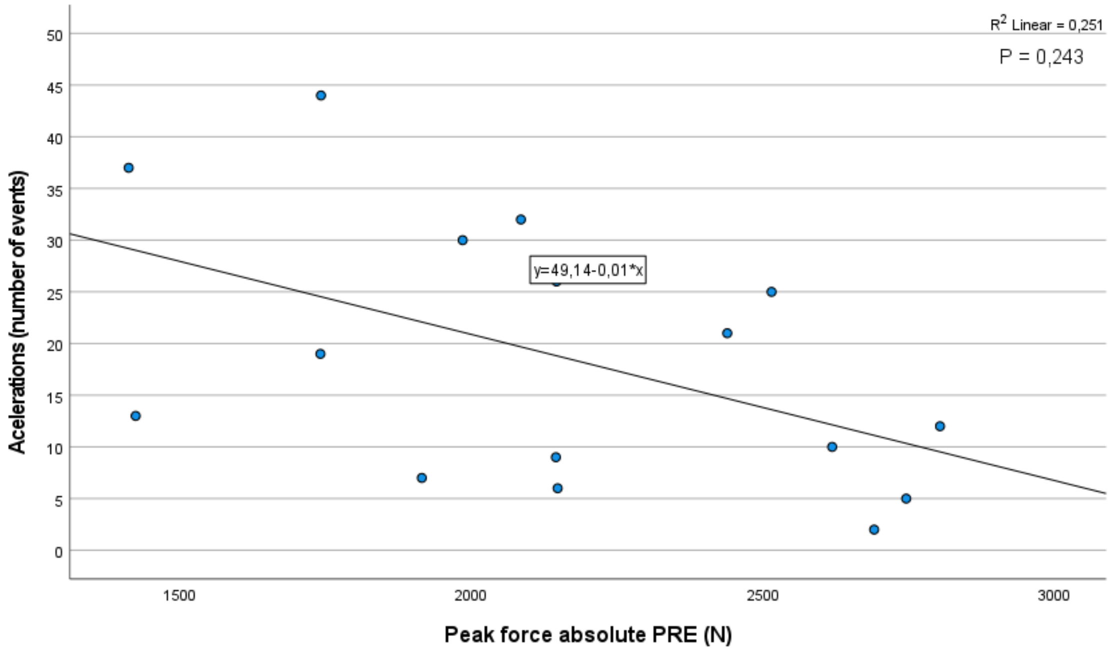
5.1.2 Correlation between Peak force absolute PRE and Distance Z2



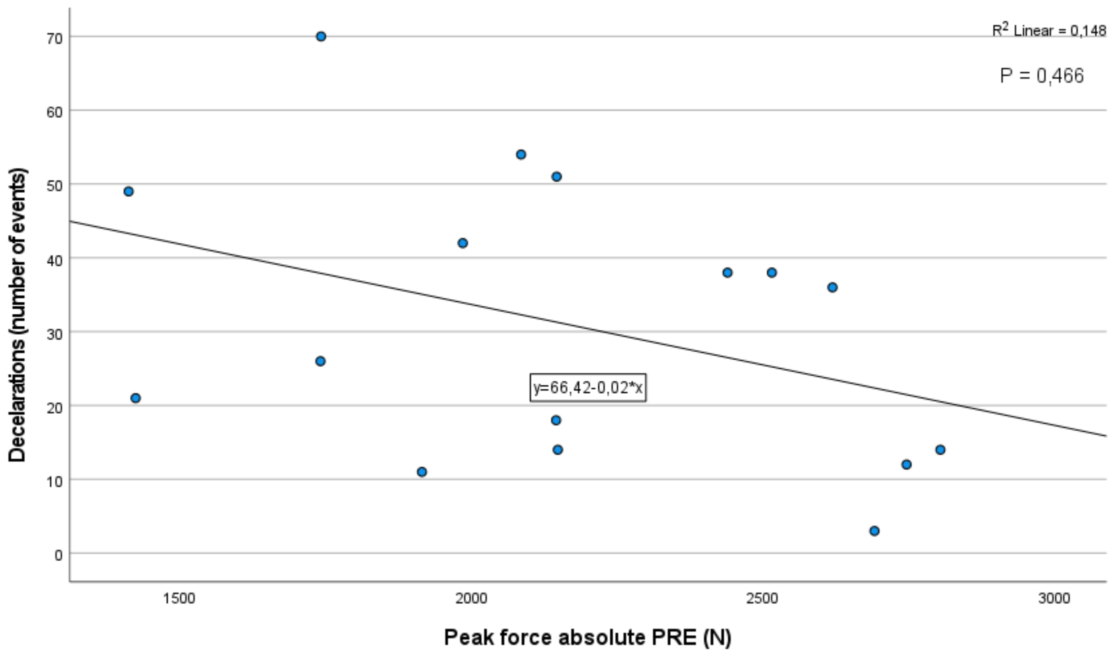
5.1.3 Correlation between Peak force absolute PRE and Distance Z3



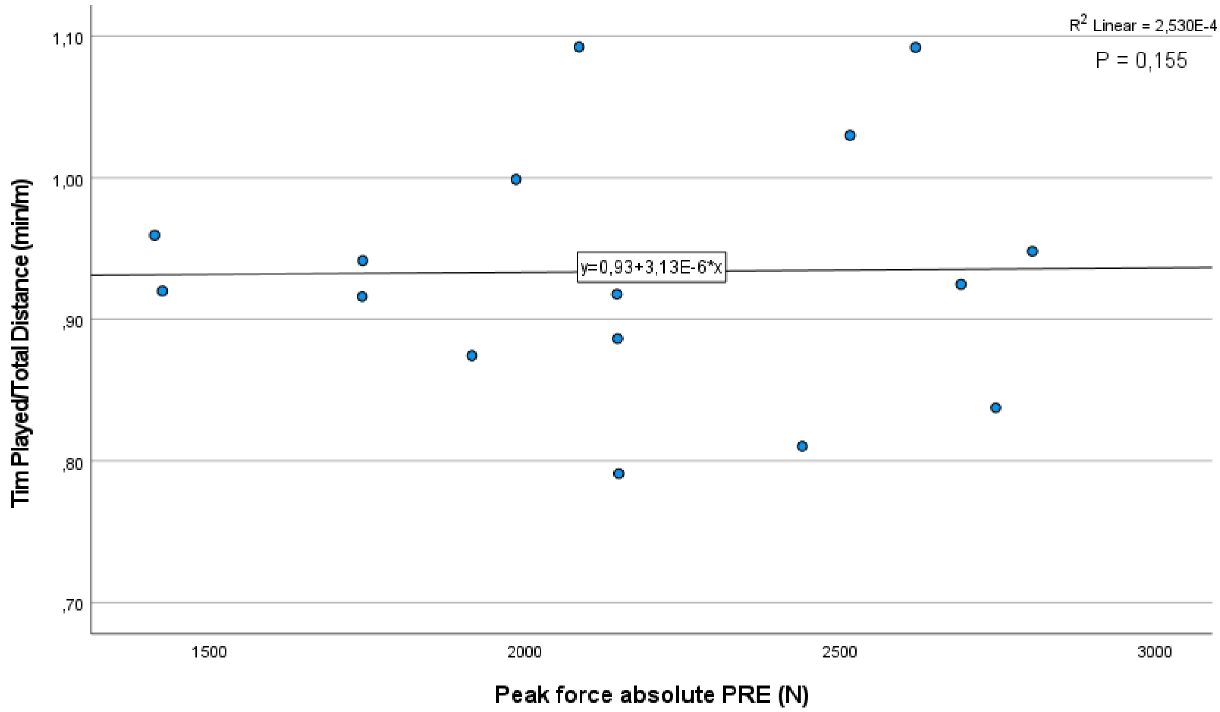
5.1.4 Correlation between Peak force absolute PRE and Acceleration



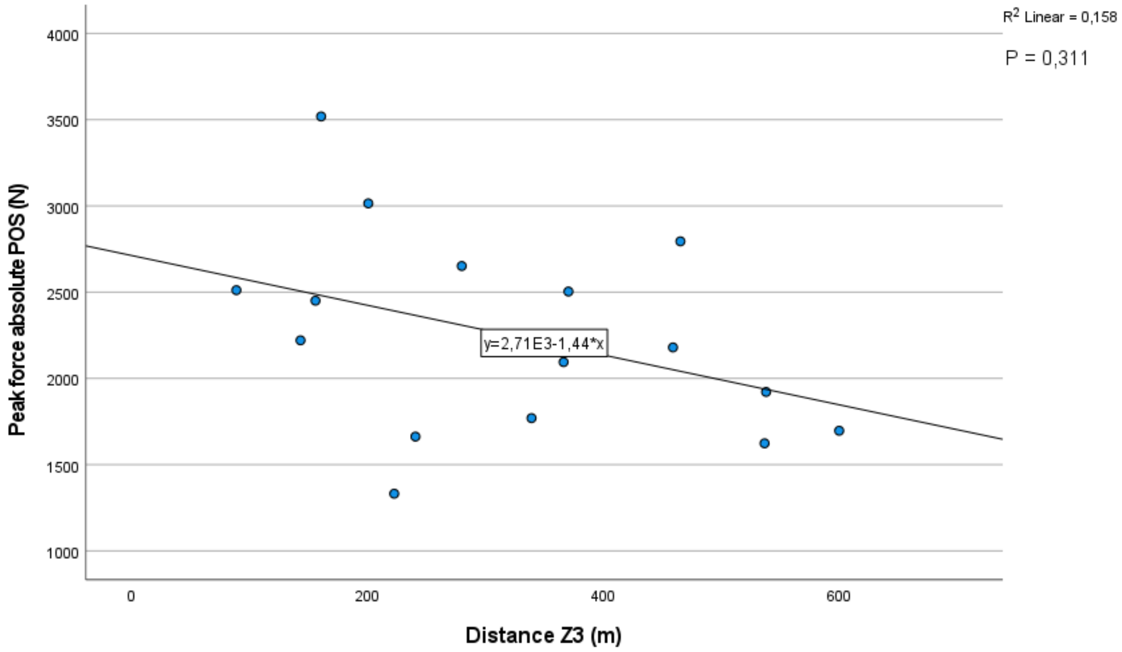
5.1.4 Correlation between Peak force absolute PRE and Decelerations



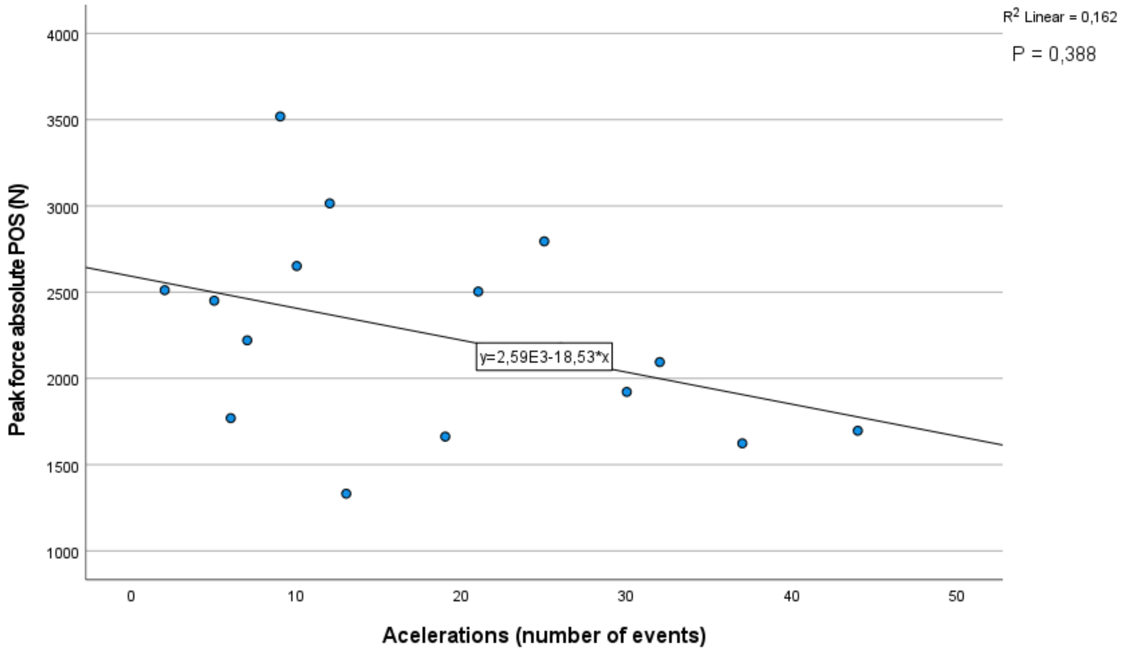
5.1.6 Correlation between Peak force absolute PRE and TimePlayer/TotalDistance



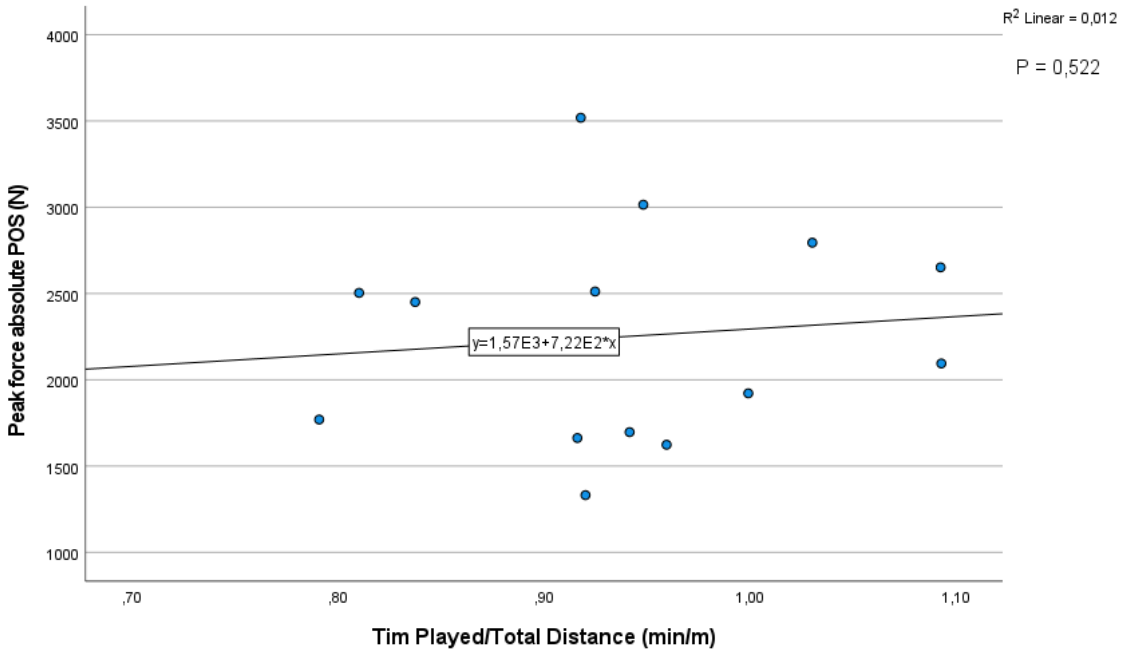
5.1.7 Correlation between Peak force absolute POS and Distance Z2



5.1.8 Correlation between Peak force absolute POS and Accelerations

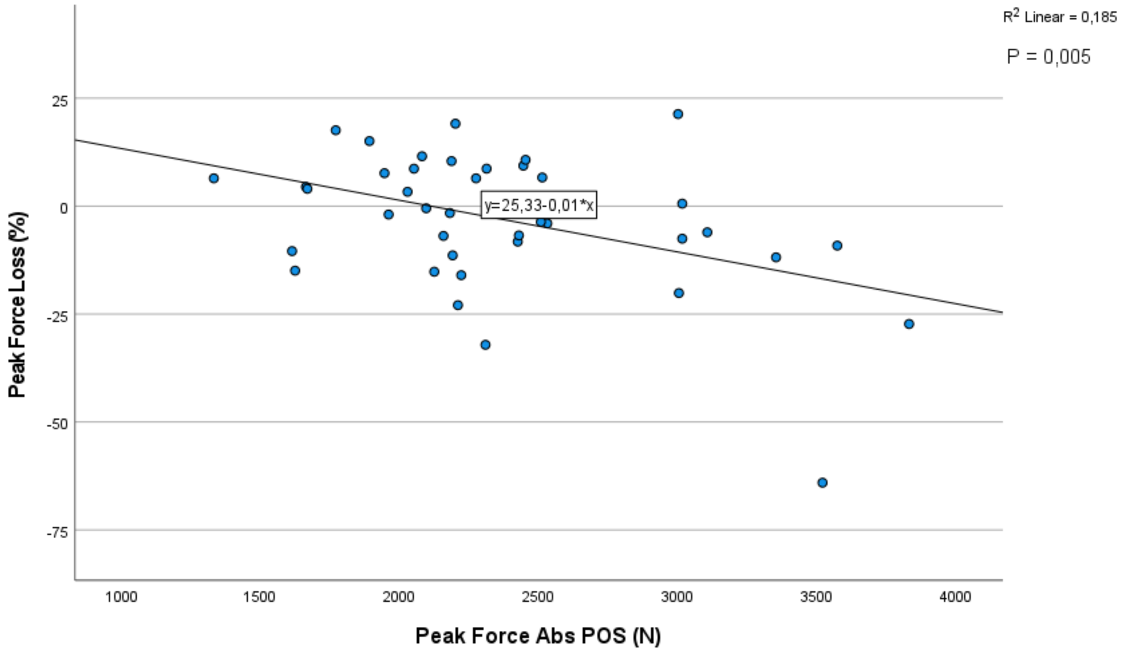


5.1.9 Correlation between Peak force absolute POS and Time Played/Total Distance

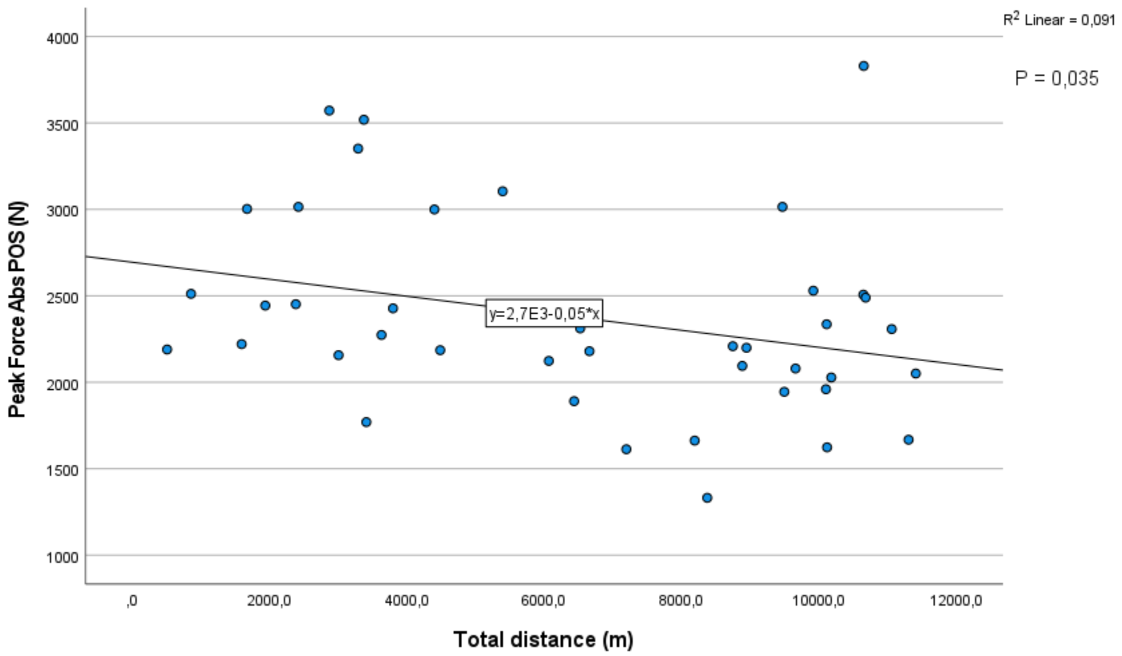


5.2 Correlation and regression analysis (all games after familiarization)

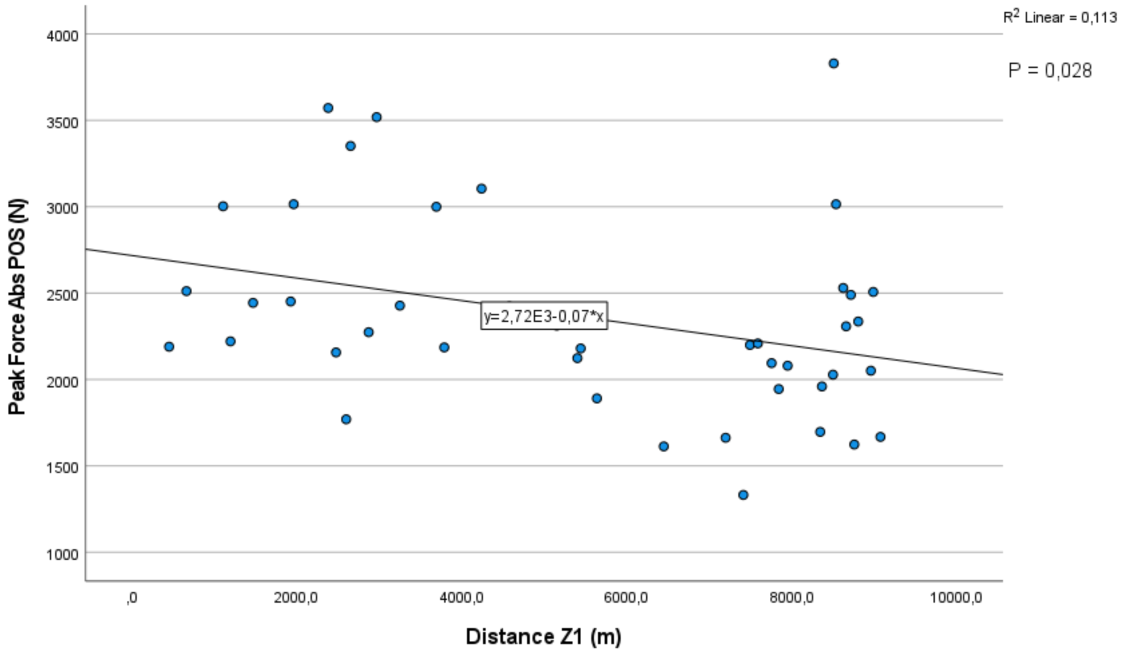
5.2.1 Correlation between Peak force absolute POS and Peak Force Loss



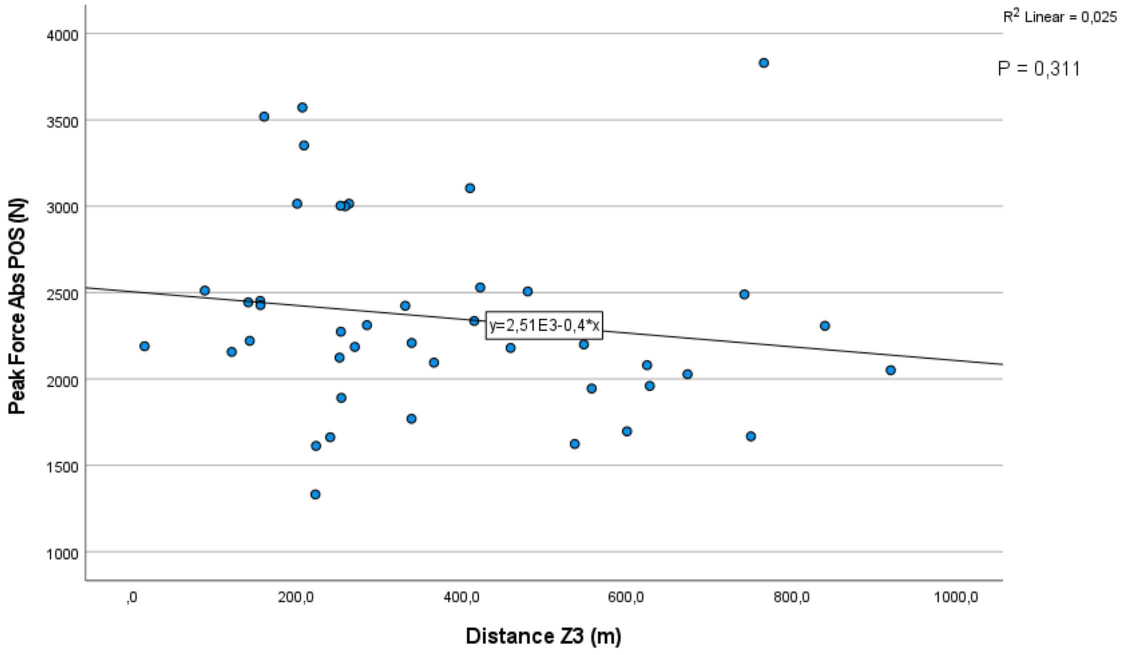
5.2.2 Correlation between Peak force absolute POS and Total Distance



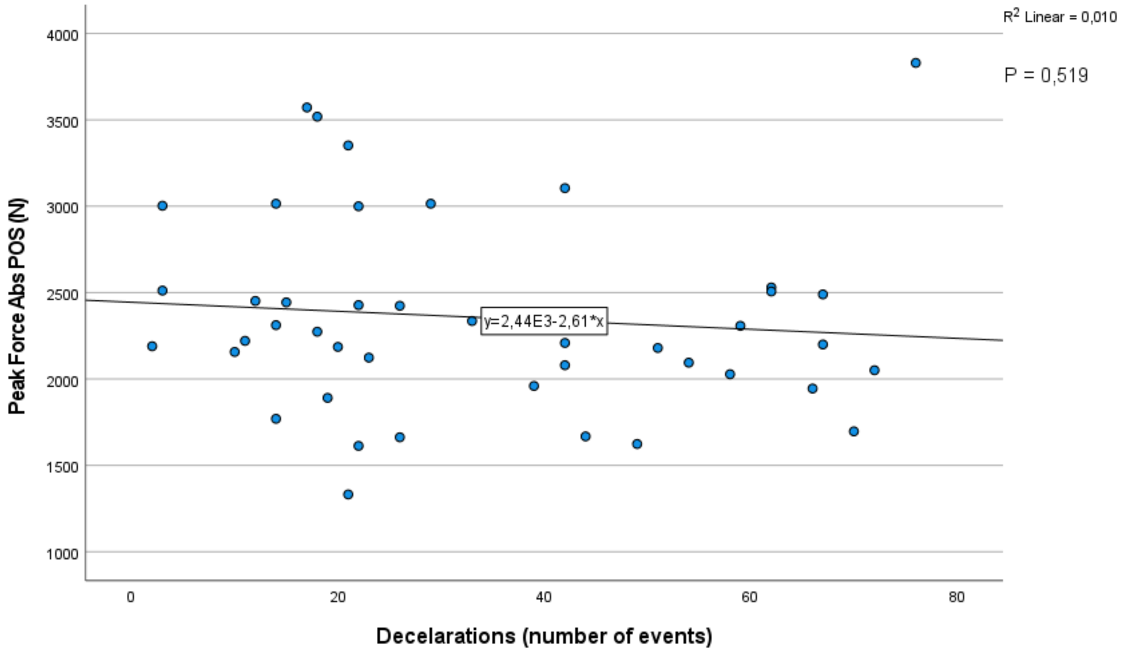
5.2.3 Correlation between Peak force absolute POS and Distance Z1



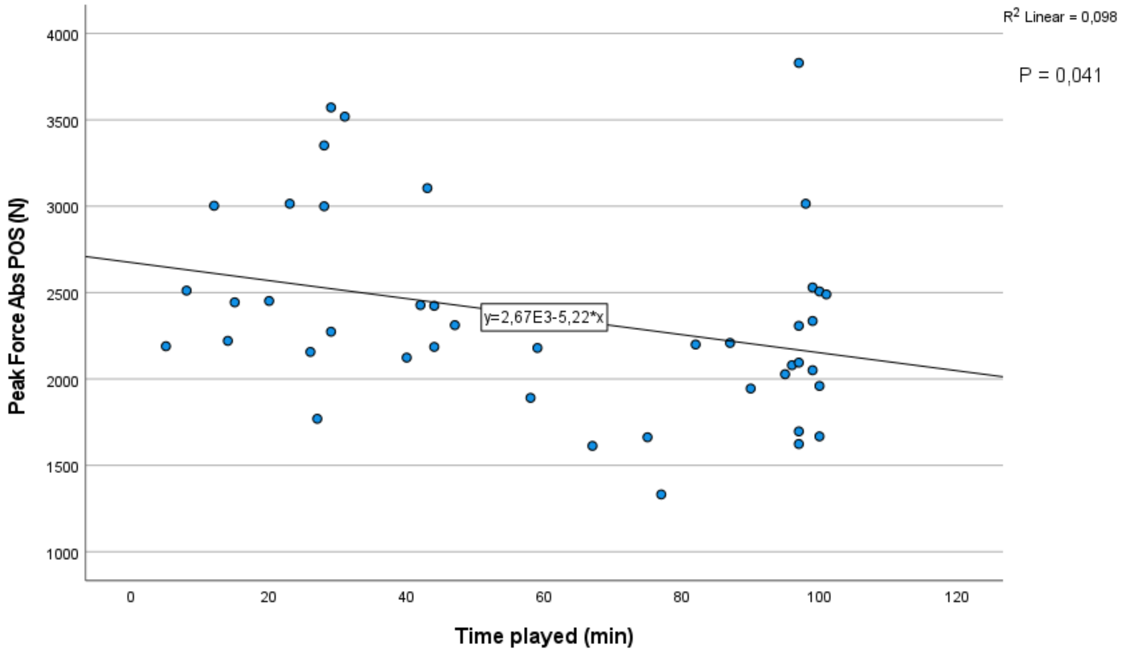
5.2.4 Correlation between Peak force absolute POS and Distance Z3



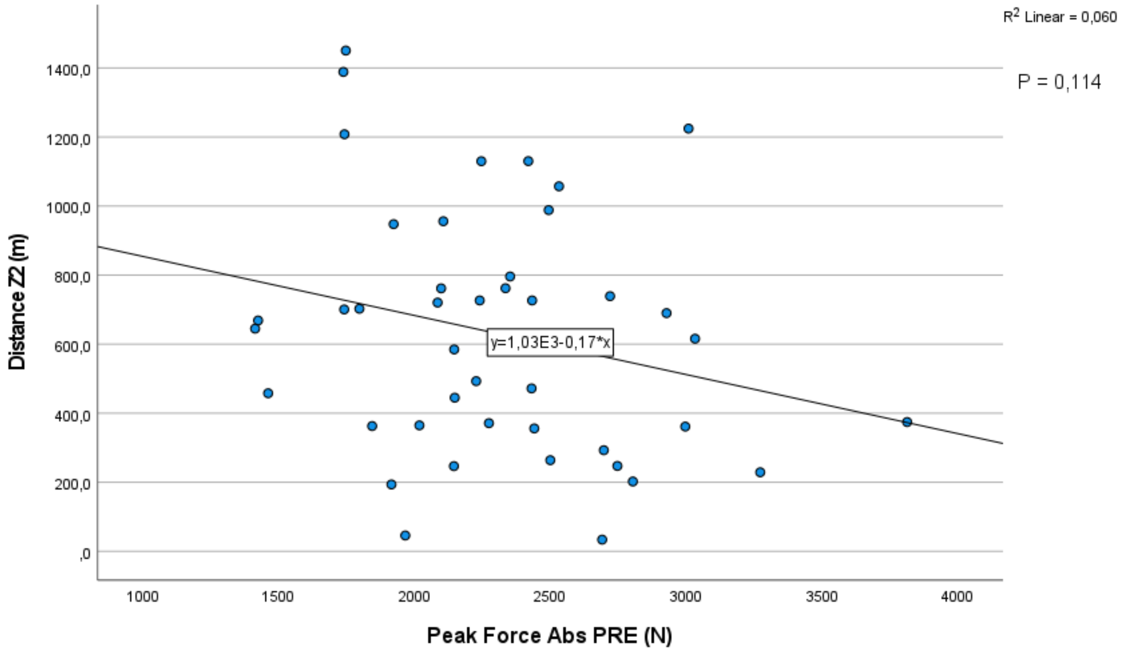
5.2.5 Correlation between Peak force absolute POS and Decelerations



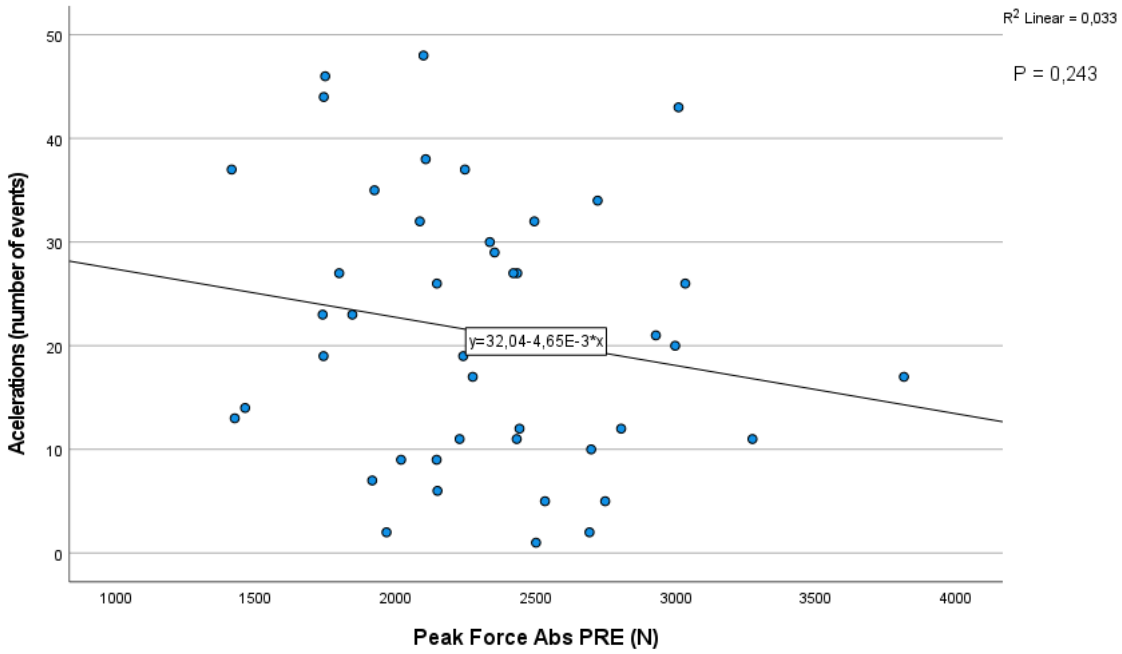
5.2.6 Correlation between Peak force absolute POS and Time played



5.2.7 Correlation between Peak force absolute PRE and Distance Z2



5.2.8 Correlation between Peak force absolute PRE and Accelerations



5.2.9 Correlation between Peak force absolute PRE and TimePlayed/TotalDistance