UiT The Arctic University of Norway

Faculty of Health Sciences – School of Sports Sciences

Training and influence of maximal strength in football players

With specific emphasis on females

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List of papers

Paper I:

Pedersen S, Welde B, Sagelv EH, Heitmann KA, Randers MB, Johansen D, Pettersen SA. Associations between maximal strength, sprint, and jump height and match physical performance in high-level female football players. *Scand J Med Sci Sports*. 2021; 00: 1– 8. Doi.org/10.1111/sms.14009

Paper II:

Pedersen S, Heitmann KA, Sagelv EH, Johansen D, Pettersen SA. Improved maximal strength is not associated with improvements in sprint time or jump height in high-level female football players: a cluster-randomized controlled trial. *BMC Sports Sci Med Rehabil*. 2019; 11, 20. Doi.org/10.1186/s13102-019-0133-9

Paper III:

Sagelv EH, Pedersen S, Nilsen LPR, Casolo A, Welde B, Randers MB, Pettersen SA. Flywheel squats versus free weight high load squats for improving high velocity movements in football. A randomized controlled trial. *BMC Sports Sci Med Rehabil.* 2020; 12, 61. Doi.org/10.1186/s13102-020-00210-y

Paper IV:

Pedersen S, Johansen D, Casolo A, Randers MB, Sagelv EH, Welde B, Winther AK, Pettersen SA. Maximal strength, sprint and jump performance in high-level female football players are maintained with a customized training program during the COVID-19 lockdown. Front. Physiol. 2021; 12, 623885. Doi.org/10.3389/fphys.2021.623885

Supplementary analysis I

Changes in physical match play performance on a subsample from *paper II*, 2019.

Supplementary analysis II

Baseline analysis on data from *paper II* and *paper III*, 2019-2020.

In this thesis, the papers and analysis listed above will be referred to by their Latin numbers.

Paper portfolio change statement

The outbreak of COVID-19 has had a severe impact on the research community as well as the rest of the world, with research laboratories being closed. The pandemic has also had a major impact on the athlete population, with lock down of training grounds, gym facilities, team sport trainings and match-play. Due to this situation, the following changes were made to the initial plan of this thesis to make the best out of the situation. This consisted of three steps:

1. Originally, one more team was to be included in *paper I*, where two matches were played, and the familiarization to the half-squat exercise was completed at the point of the lockdown 12th of March 2020. This team would have given an additional n=10 players, plus another match for most of the players. However, it was difficult to ascertain the duration of the lockdown, and with the time constraints of a PhD project, the decision was made to continue without the team.

2. *Paper IV* was originally planned to study the effect of muscle mass and body composition on physical match play performance. The body composition data was planned to be associated with the laboratory tests as well, where we would investigate whether muscle mass, muscle strength, or muscle strength/muscle mass influences ump and sprint ability, as well as physical match play performance. At the point of the lockdown, only one team had performed their DXA scan tests, and this data is presented as descriptive in paper IV. Further, one test day on the training field was cancelled due to COVID-19. For this test day, a 30 m sprint test as well as an agility test was planned.

3. *Paper IV* was changed to investigate the effect of the restricted training environment on the already collected data from one week prior to lockdown in March. We subsequently performed a second round of testing prior to the summer holiday in June 2020.

Abbreviations

1RM - One repetition maximum

ACC - Acceleration count

ANOVA - Analysis of variance

BFW - Barbell free weight training group

CG - Control group

CMJ - Counter movement jump

COD - Change of direction

CV - Coefficient of variation

DEC - Deceleration count

DXA - Dual energy x-ray absorptiometry

FIFA - Fédération Internationale de Football Association

FW - Flywheel training group

GPS - Global positioning system

ICC - Intra class correlation

MHCI - Myosin heavy chain I

MHCII - Myosin heavy chain II

MST - Maximal strength training

OC - Oral contraceptives

ROM - Range of motion

SD - Standard deviation

Sprint 5 m - 5 meter sprint time

Sprint 10 m - 10 meter sprint time

Sprint 15 m - 15 meter sprint time

TG - Training group

U20 - Under 20

VO_{2max} - Maximal oxygen consumption

YYIR1 - Yo-Yo intermittent recovery test

YYIE2 - Yo-Yo intermittent endurance test

1 Introduction

Football is the most popular sport in the world (1). For health and as medicine, football is considered a joyful, social activity that is effective and valuable for nearly all types of people across nearly all ages (2). Professionally, both males and females participate in football, and it is a large profitable entertainment industry (3) with a growing live telecasting, which in turn has increased the revenue of the clubs (4).

Over 30 million women and girls participated in football in 2015 (5), an increase of 32% since 2010 (6). Moreover, the last Women's World cup reached an exceptional and record breaking numbers of spectators, TV-viewers and attendances (7), illustrating its growing recognition. During the last two decades, the competitiveness of elite women's football has evolved considerably, approaching the status of men's (8). However, the sex gap in sports persists, being affected by reduced opportunity and sociopolitical aspects that influence full participation (9).

Regulating strategies have been recently implemented which have contributed to the growth of female football. Fédération Internationale de Football Association (FIFA) has dedicated a 1 billion USD investment during 2020-22, in an effort to accelerate the development of women's football (10). As such, female football is experiencing increased professionalization, providing both players and coaches the opportunity to make it a full-time career (11). This professionalization and increased participation of females has slightly decreased the performance gap between sexes (12).

Football is considered the most studied sport in the world (13). In line with the increased professionalization, research on female football players is growing as well (13). Research on performance in football usually follows reductionistic approaches, where separate characteristics often are studied in isolation. Consequently, it has been postulated that the determining factors of football performance involves technical, tactical, and physiological variables (14-16), as well as psychological characteristics (17). Likewise, physiological features (18), technical traits (19), and tactical/strategical attributes (20) have all been associated with performance in female football through research. Importantly, football is constantly evolving, where the speed of play (21), together with technical and physical demands are progressively increasing (22-24), emphasizing the need for up-to-date research on the physical demands and characteristics of the game and its players.

Although the most studied sport in the world, it is important to emphasize that in general much of the research impacting physical testing and training prescription in football has been completed on male participants (12). The generalization of such research to female athletes ignores the inherent biological differences between sexes (25). Therefore, additional research on the physical demands, diagnostics, and training for female football players is needed, based on data provided from female football players.

1.1 Physical match play performance

A conceptualization of the difference and connection between physical match play performance and physiological responses in team sports were put forward in 2003 by Tom Reilly, through the presentation of the internal and external training load concept (26). External load (physical match play performance) during training and match play is relatively simple to monitor through use of technology (27), while the internal load is the physiological and psychological response to the external load (28). The rapid development and wide-spread adoption of athlete-tracking devices are increasing (29), where global navigation satellite systems (GPS) and local positioning systems (LPS) are commonly applied in the daily training and match play of elite football clubs. Research deriving from such tools have expanded the body of knowledge regarding physical match play performance, and hence insights about the demands of the game. Tracking of typical variables of physical match play performance and thus external load include total distance covered, high intensity running, and sprint distance covered, number of accelerations and decelerations as well as peak sprinting speed (30, 31).

Generally, female football players cover slightly less total distance during a football match than male players (10754 m vs 11142 m) (32, 33). Further, total distance covered does not deviate between competitive levels (34), which suggest that locomotor distance covered at low intensity, or the volume of meters covered, is arguably not an accurate indicator of a player´s standard. However, the volume of running at high intensity is of greater importance (35). High intensity running comprise from 700-1300 m (5, 36-38) (>~16 $km \cdot h^{-1}$), and sprinting (> 20 $km \cdot h^{-1}$) constitute from 200 to 900 m (5, 37-39) of the total distance travelled per match. Originally, players performing at higher competitive levels display greater volumes of high intensity running and sprinting during match play than players of lower competitive levels (34, 37, 40). However, this finding has been recently questioned when examining the difference between international and domestic level players (31), where small differences were found. Importantly, based on the observation that male football has experienced an increase in high intensity running and sprinting in the premier league (23), and that female football is constantly evolving, these measures of physical match play performance are expected to improve further, as hypothesized for males (24).

Straight sprints by the scoring player is shown to precede 45% of all goals scored by male football players (41), illustrating its relevance during decisive moments in a match. Further, the relevance of short sprints are highlighted by the findings that 76% and 95% of all sprints during female match play are between 0-5 m and 0-10 m in length when neglecting the acceleration phase required to reach the cut-off speed for "sprinting", respectively (42). Interestingly, female players perform a higher proportion of explosive sprints compared to their male counterparts (43), which has been an argument for a performance development focus on short sprints (< 10 m) in female training (42). From male football, we know that power and speed abilities are important within decisive situations in professional football, and should be included in fitness testing and training (41).

A less studied variable of physical match play performance is acceleration. The number of accelerations during a match seems to be a more stable and sensitive measure of physical match play performance compared to other variables (44), and appears to be affected by a fatiguing competition schedule to a greater extent than high-intensity running distance (45). Importantly, accelerations are indicative of performance level, as illustrated by elite senior players performing more accelerations and decelerations per match compared to U20 female players (37). In the literature, descriptions of acceleration and deceleration in elite female football players have a substantial variation probably due to methodological differences between studies (6), with between 160 to more than 400 accelerations and decelerations per match reported (36, 37, 46).

All these match-related demands will require certain physiological characteristics from the players, in order to meet the demands of match play (47). For example, considering the short distances used to accelerate and decelerate, players must absorb and produce high forces imposed on the neuromuscular system (6, 48). Importantly, knowing which and how the different physiological traits influence performance during the competitive sporting context should be fundamental for athletes and coaches. Moreover, most of the current understanding of the demands is based on studies conducted on male football players. An example of this can be illustrated by Emmonds, Heyward and Jones (49) in 2019, where a search of literature from the last decade using the term "soccer match demands" combined with either "male" or "female" yielded 102 and 13 articles, respectively. Although most of the research on the demands in football are derived from male players, a growing body of science investigating female football is emerging. Nevertheless, more research on the physiological factors that are important for female football players is warranted. An understanding of individual player's physical capacity is important for team selection, and for specific training programming and utilization (18). To date, important factors such as VO_{2max}, high-intensity intermittent endurance capacity, sprint speed, strength, and jump capability have been proposed as relevant targets (18).

It is important to recognize that physical match play performance in female football is influenced by several other factors than just the fitness level of the players in the team. Player opposition is one of these factors, where increases and decreases in accelerations of 10% are reported after either playing against higher ranked teams, or playing as highly ranked teams against lower ranked teams (50). Further, greater sprinting distance is observed when teams are losing a match (51). Environmental factors such as altitude (50) and temperature (50, 52) also affect match physical match play performance, as well as tactical aspects such as player position (39, 42) and whether or not the team is in possession of the ball (42). Further, findings of more high intensity running being performed on a synthetic turf vs natural grass (51) makes the picture more complex.

1.2 Female football

The increasing professionalization in female football has resulted in players gaining access to improved training conditions and modern fitness training facilities, medical provision and support of strength and conditioning professionals (31). In turn, these changes have broadened the possibilities for training and recovery of female football players. However, the application of evidence-based practice should be impacted by and obtained from the scientific literature, which given the shortage of research in female athletes, produces a challenging task

(49). When basing our presumptions on which tests to use for female football players, a large amount of our underlying knowledge comes from male football research. As stated by Mujika and Taipale (12) in their editorial titled "Sport Science on Women, Women in Sport Science": *"it is also worth remembering that much of the research used for exercise testing and prescription…has been completed on male participants"*. For example, a recent review investigating the relationship between physical and physiological testing, with physical match play performance, consisted of a sample of 964 male football players but only 27 female football players (53). Thus, the body of knowledge relating tests and physical traits to physical match play performance is almost exclusively based on research on male players, who are physiologically different from females. For example, when investigating the differences in physical capacities between male and female elite players from the Bundesliga in Germany, the largest differences between sexes were explosive traits such as sprint and jump ability (54). Therefore, more studies on the relationship between tests of strength and explosive qualities and physical football performance in female football players are necessary.

1.3 Physiology in female football

The aerobic system is highly taxed during football match play, where approximately 98% of the energy is derived from aerobic metabolism (55). Consequently, lower level players show lower maximal oxygen consumption (VO_{2max}) values than higher level players (18). Moreover, VO_{2max} is more stronger correlated with high-intensity running during match play for female (56), than for male players (57). Intermittent endurance has generally been tested with the Yo-Yo intermittent recovery test (YYIR1), or the Yo-Yo intermittent endurance test (YYIE2) in female football players. Large differences in performance have been observed between first and second division players, for the YYIR1 test (58), as well as between elite, domestic, and sub-elite players for YYIE2 test (59). Repeated sprint ability is also shown to reflect the most intense part of the match, and separates players from different levels of competition (60). Together with the measures of football endurance capacity, the ability to perform forceful and fast movements is considered critical for football players (55).

Although the major proportion of a football match comprises low and medium intensity activities (61), actions such as sprints, jumps, duels, and kicking are crucial actions for football performance (62). Strength is defined as the maximal force a muscle or muscle group can generate (63), and together with power is suggested to be equally important as endurance in football (55). It is recognized that in order to accelerate high concentric strength of the leg extensors is necessary (64), and maximal strength is related to sprinting and jumping ability, at least in male football players (65, 66). Therefore, jumping and sprinting have received the tag “strength derivatives” (14).

The latest review on physiology of female football players emphasizes that limited research into muscle strength exists for females (18), a notion that was highlighted a decade earlier in a similar topical review (55). This is surprising, given that female football players consistently carry out strength training as a part of their practice (67), which in this regard is conducted with little scientific support. Hence, it is relevant to study to what extent, if any, muscular strength has on performance within specific sport settings (68), as well as how strength training and manipulation of strength levels affects female football players.

Although elusive, there are indications of strength being associated with performance level in female players, illustrated by superior isokinetic leg strength in starting players compared with non-starters within an international female team (69). This is in line with findings from male football players, where half-squat dynamic strength was higher for the best team compared with a team from the lower half in a professional league (70). However, other research did not find a difference in leg strength between international and regional female football players in England (71). To the author’s knowledge, associations of strength with match play has only been studied in males, where certain strength variables are connected with fatigue resistance during play (72). Hence, the importance and impact of strength for performance level have not yet properly investigated and remain inconclusive for female football players.

Power is force produced divided by time (14). Muscular power has conventionally been assessed by vertical jump height in football players (14). As an example, the counter movement jump (CMJ) is a commonly applied test (55). Differences in CMJ (8-14%) have been reported between national-team players and first division players (73), as well as between junior and senior level players (74), indicating that CMJ performance allows differentiation between the levels of competition in female football players. However, other research has not found differences in jump ability between female elite and sub-elite players (75), which confound the relevance. Further, studies of the association between CMJ and physical match play performance has to the best of the author's knowledge only been conducted using male football players, with inconclusive findings (72, 76-79).

Sprint performance is an important attribute for football players. It has been shown that sprint tests can distinguish female players of different competitive levels (80), and age classes (81). Likewise, players selected for inclusion in talent identification projects and drafts have demonstrated superior 5 m and 10 m sprint results compared to the non-selected players (82, 83). Others researchers did not find statistically significant differences between the starters and non-starters within a team, although it was concluded that the non-significant 10 m sprint time difference of a meaningful magnitude (84). When comparing international level vs domestic level female football players, 5 m and 10 m sprint times were only different within defensive central midfield position (31), indicating that the importance of these physical characteristics may be position dependent at the higher levels. Nevertheless, the ability to sprint quickly over short distances seems to be important in female football. To the best of the author's knowledge, only a handful of studies have investigated the association between sprint tests and physical match play performance and have being limited to male players (72, 79, 85).

In summary, strength, jump, and sprint abilities, together with endurance capacity are considered important and relevant factors for football performance. However, in contrast to endurance capacity (56), less is known about how strength, jump and sprint abilities relate to physical match play performance in female players.

1.4 Testing, training, and detraining of high force and high velocity traits in football

Studies have been carried out to find the most suitable physical tests for football players, which will offer valuable information for training prescription and monitoring (86, 87). To ensure that data assessed from tests are pertinent to real life match play performance, high ecological validity is necessary. For football, this can be physical match play performance derived from tracking data (78). The next step is to study the associations between test results and physical match play performance (53). These tests could result in physiological parameters measured, either in the laboratory, or from field tests, being close to the practical sport setting. In general, field tests have been applied by coaches due to their conventional nature. However, as with all reductionistic approaches in football research, it is imperative to state that no single field- or laboratory test will be able to determine performance during football. It is challenging to individually study the importance of single physiological factors as the overall demands of football are very complex due to it being an open loop sport (86).

1.4.1 Strength

A consensus statement from 1990 concluded that "males and females should train in the same basic way, employing similar methodologies, programs and types of exercises" (88). The finding of a similar gap in strength levels between sedentary controls and football players of both sexes, has been raised as an argument that there are no relative differences in strength training status between male and female football players (89). Importantly, a recent meta-analysis on the effect of strength training on jump height and linear sprint performance in female football players concluded that more research is needed in this field (90).

It has been suggested that female football players appear to possess insufficient strength to be able to absorb forces generated from football specific movements optimally (91). Surprisingly, there are only limited interventional studies involving maximal dynamic strength as an outcome variable for female football players (92). On the other hand, it is shown that in practice, female football teams prioritize strength training in the preparation period in order to increase strength prior to the competitive season (67). Hence, controlled studies of strength training could potentially guide the practice field towards optimal training strategies for female football players.

There is no consensus on a gold standard protocol for testing of strength in football players in general (1). Dynamic strength measurements, such as one repetition maximum (1RM) applying free barbells will reflect the specific strength of football players (37) and may thus be included in training studies. There are nevertheless several studies applying isometric strength measurements (22, 24, 25) which do not consider that strength reflects the type of training carried out (45). For example, an observed increase in isometric strength is not necessary indicative of dynamic strength improvement (25). Isokinetic testing reflects the force generated by a muscle against a resistance at a constant rate of movement (44) and has been applied in male football players (23). However, as no notable natural muscle movement in football seems to be isokinetic, this method may poorly reflect the movements carried out in the sport and consequently have low specificity (1). Furthermore, few studies have reported strength variables for female football players as an outcome of an intervention, demonstrating the lack of research on the practical manipulation of strength levels for female football players.

Muscular strength can be increased by either muscular hypertrophy or neural adaptations (14). During the last two decades, maximal strength training (MST) has proven effective for strength increases in performance and health research (93-96), and is characterized by heavy load (≥ 85% 1RM), maximum intended velocity during the concentric phase, long rest intervals (> 3 min) and relatively low volume and few repetitions (3-5 sets x 4-6 repetitions) compared to conventional hypertrophy training (10-12 repetitions,~60-70% 1RM, 3-4 sets and controlled movement speed). Furthermore, MST is shown to be more effective for improving strength and rate of force development (95), as well as sprint and jump ability (97) compared to conventional hypertrophy training in males. This training is aiming at improving strength primarily through neural adaptations with minimal hypertrophy gains (98, 99).

Traditionally, training regimes for developing speed and explosiveness have mainly consisted of training in the right spectrum of the force velocity curve (repetitions with high velocities and low loads) (6). Elements of this training is characterized as plyometric or ballistic exercises. Typical plyometric exercises are box jumps, hurdle jumps or drop jumps where there is no to low external loads, in contrast to strength training with high external loads. Although the repetitions during MST are performed with high loads, resulting in low external velocity of movement, one may still observe improvements in muscle power and especially rate of force development (14, 100), as well as jump and sprint performance (99) (*i.e.* strength derivatives) (101). A suggested mechanism behind these adaptations is that the intended velocity, rather than the actual velocity during the movement decides the training response, where the neural drive to the muscles involved is improved following training (100).

In the design and planning of strength training, numerous factors can be manipulated, such as: exercise selection, intensity, contraction velocity, number of repetitions, sets, and duration of recovery intervals. Young, Benton, Duthie *et al.* (102) recommended employing free weights during training to improve sprint performance over the acceleration phase. This suggestion has been supported by other researchers that advocate dynamic strength training (55).

Moreover, to create a situation where high forces can be developed, the athlete must be stable, as seen with for example the half-squat exercise (103).

Further arguments for the choice of exercises are the distinct biomechanical differences between short sprints, which indicates acceleration speed, and longer sprints, which may capture peak speed, which have implications for muscle groups and strength qualities that are required in each type of sprint. For example, knee extensor muscle activation is higher during the first 5 m of a sprint than exceeding 30 m (104). Hence, it has been argued that modalities targeting the quadriceps more than the hip extensors may be more specific to short sprints compared to longer sprints (102).

Changes in range of motion during the squat exercise can affect the quantity of external load possible to handle, with partial range of motion (ROM) loads being far greater than the full ROM (105), which again can affect muscle activation (106) and in turn, the training effect. Moreover, the specificity of ROM can be demonstrated by the adaptations being limited to the ROM performed during training (107-109). For the squat exercise, strength coaches usually categorize the ROM based on the degrees angle of the knee joint: partial squats (40 degrees), half-squats (70 to 100 degrees), and deep squats (> 100 degrees) (110). As most of the research conducted with MST applying half-squats or leg press for males has demonstrated a transfer effect to other functional performance traits as jump and/or speed capacity (14, 55, 98, 99), it seems reasonable to investigate the effect of this training model further in female football players.

In addition to improving strength, sprint speed and jump height, MST has shown to improve running economy in football players (14). This has implications for football players intermittent performance. For example, MST has been found to be superior to hypertrophy training for strength gains, and consequently was the only group with an improved work economy, which again resulted in a tendency for a larger improvement in the intermittent endurance tests for males (111). Hence, as the intermittent endurance tests are associated with high intensity running distance during match play both for male and female players (56, 112), increased strength by MST may have the potential to improve the ability to perform high intensity running and sprinting during football match play in females. Indeed, there are indications that strength is related to physical match play performance, where negative associations between isokinetic strength of leg extensors and flexors with decrements in high intensity running during match play have been observed (72). The authors concluded that greater levels of lower-limb strength was related to a better ability to maintain performance during match play (72). However, these findings should be replicated with dynamic maximal strength tests, and for female football players.

1.4.2 Jump ability

Along the same lines, associations have been identified between CMJ tests and intermittent endurance tests (113), and repeated sprint tests (114), both of which are designed for their specific relevance to intermittent team sport play. Interestingly, one study showed a strong relationship between YYIR1 performance and CMJ height for female players ($r = 0.6$), while they were not related in males (74). Given the strong relationship between YYIR1 and high intensity running ($r = 0.76$) during match play for female football players (56), CMJ could potentially be related to high intensity running.

1.4.3 Sprint ability

There seems to be differences in how male and female football players develop running speed. For example, research that has investigated the seasonal variation in physical fitness measures of male players have shown improvements in sprint and jump height performance from the initial period of preseason to midseason (115). After midseason, sprint performance remains stable to the end of the season (115). On the other hand, sprint characteristics in youth female players have been shown to remain unchanged or decline across the course of the season (67, 116). Interestingly, and in line with the observation of small seasonal changes in sprint ability, cross sectional data suggest that female football players appear to have more difficulty in improving sprint velocity from junior to senior age than their male counterparts (73, 117, 118). These studies suggest there could be sex differences in seasonal variations for sprint performance. Following this concept, and acknowledging the importance of short sprinting in football (42), a recent systematic review and meta-analysis pointed out that research utilizing short distance sprint performance as an outcome across the whole football code (football, rugby) was mainly undertaken with male football players where some form of tertiary training methods (*e.g.*, strength, power, and plyometric training) was implemented (119). Thus, there are discrepancies regarding what are the best practices to improve female football players' sprint speed due to the lack of studies (90).

1.4.4 Detraining

Detraining is defined as a "partial or complete loss of training-induced adaptations, in response to an insufficient training stimulus" (120). In the annual periodization of the training plan, development and maintenance of different traits are emphasized for different periods. For example, one main objective of the pre-season phase in football is to maximize fitness parameters like jump and sprint ability as well as maximal dynamic strength (121). Indeed, strength training volumes in female football are shown to be higher during pre-season compared to the competitive season (67). When season approaches, more emphasis is put on other important areas such as tactical and technical training, as well as recovery from weekly competitions (67, 121). Furthermore, the total training volume is usually reduced from pre-season to competitive season to provide freshness for competitions (67, 122). These adjustments in training can lead to specific physical qualities being undertrained during the competitive period, resulting in a detraining effect.

Loss of strength, speed, and jump performance would be detrimental for football players. During extreme inactivity such as bed rest, where no exercise stimulus or physical activity is present, a muscle strength loss of 40% is evident after four weeks (123), displaying the malleability of contractile tissue and function in the human body. Rønnestad *et al.* (121) observed an initial improvement in maximal strength, and consequently sprint performance following MST, where a subsequent reduction MST volume and frequency led to decreased maximal strength and deteriorated sprint performance for male football players. Moreover, deterioration of physical qualities such as 5 m and 15 m sprint time, and maximal dynamic strength, during the competitive phase of the season has been reported for female players (67, 124), probably mirroring the reduced focus on physical training during the competitive period.

Following COVID-19, numerous researchers hypothesized training cessation and consequently detraining effects for athletes engaging in top sports (125, 126). The emergence of COVID-19 resulted in local lockdowns and the closure of training facilities, including both private and commercial gyms (127). These facilities are necessary to undertake MST in the form that was described earlier this chapter. The maintenance of physical quality seems dependent on its training status (121). It has been speculated that athletes participating in team-sports, where the multiple physiological and physical match play performance variables are important, may maintain general fitness through methods such as circuit-based training (127). Nevertheless, to maintain strength, sprint and jump abilities, little data exists on the proper training regimes required during periods of lockdown.

2 Aims of the thesis

The main purpose of this thesis was: to investigate the relationship between maximal strength and physical match play performance in female football players; the effect of including or excluding systematical MST on strength derivatives (sprint and jump ability); and to compare these results in the light of findings in male football players. A proposed framework of how the different research questions align with football performance is illustrated in Figure 2. This thesis contains four studies where the following research questions were put forward:

1) What are the association between strength (1 repetition maximum (1RM) half-squat strength), 5-, 10- and 15 m sprint, countermovement jump (CMJ)), and physical match play performance in high level female football players?

2) Does maximal strength training result in improvements in strength, and is it associated with improvements in sprint and jump height performance in female football players?

3) What are the effects of flywheel half-squat training versus free weight MST on 10 m sprint time, CMJ, and 1RM half-squat strength in male football players? Are the previous results reported following MST for male players reproduced in our lab? How those these findings compare with findings from *paper II*?

4) How does a prescribed unsupervised 12-week home- and group-based training program without gym facilities affect 1RM half-squat strength, CMJ, and 15 m sprint time in female high-level football players during a period without full contact football training?

In addition, two supplementary analyses (*supplementary analysis I* and *supplementary analysis II*) based on *paper II* and *paper III*, are included to (1), study the effects of MST on physical match play performance, and (2), to study the baseline characteristics between male and female football players prior to MST.

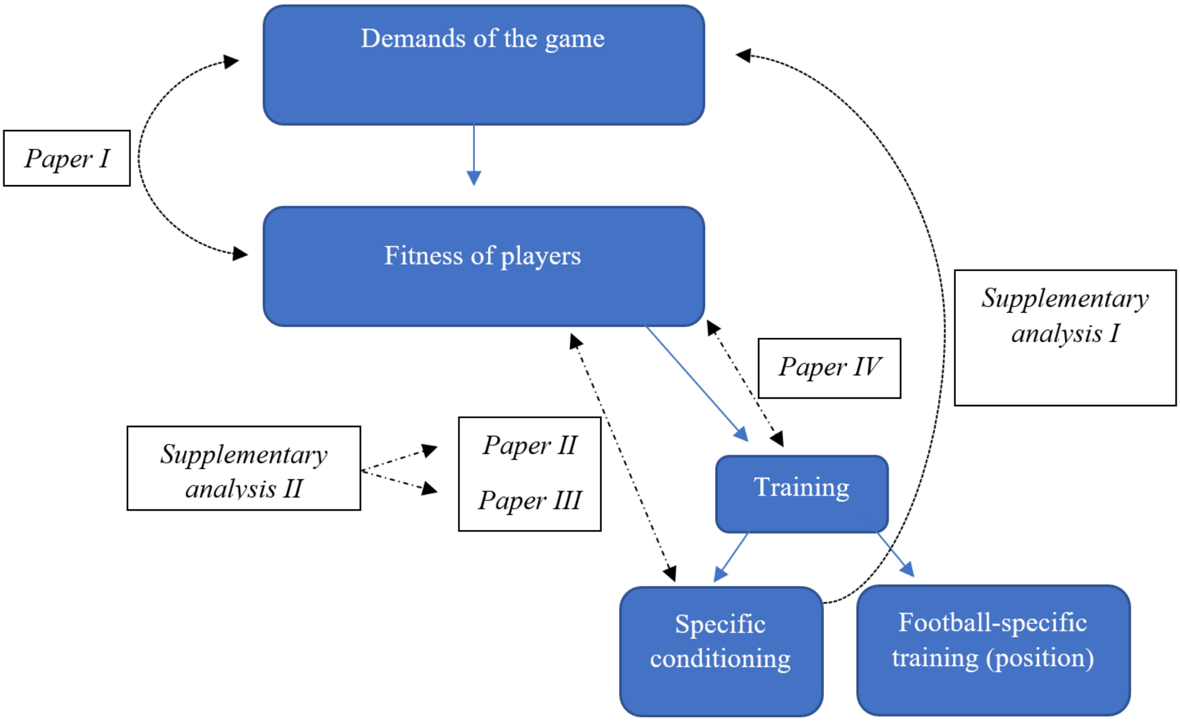

Figure 1. Amended version of "*An ergonomics model for the analysis of football*", from Reilly (47). The blue details in the figure represent the components of the model, as published originally, and reused with permission from Taylor & Francis. The black details are added by the author of this thesis, and represents the overview of the current thesis, and how it connects with the proposed framework.

3 Study population and methods

The methods described here offer a summary and the reader is referred to the original papers for more comprehensive descriptions.

3.1 Ethical considerations and confidentiality

Data collected and analyzed in the papers of this thesis were approved by the Norwegian Center for Research Data. All data was anonymized before analysis and publishing to ensure player confidentiality. For all studies, each participant signed a written and orally approved informed consent, informing them about the potential benefits and risks of the studies, according to the declaration of Helsinki. For participants under 16 years old, the parents or guardians, in addition to the participants, provided written informed consent. The regional ethical committee did not need to evaluate the project according to their mandate to not evaluate research which do not have a direct medical or health related outcome. This is manifested in the Norwegian Health and Research Act, paragraph §2 (128).

3.2 Participants

Both male and female football players are included in this thesis. Table 1 gives a descriptive overview of the participants in *paper I-IV*, whereas Tables 2 and 3 describe the participants included in *supplementary analysis I* and *II*.

Paper I study participants

Thirty-seven (n=37) female players from two Norwegian female football teams playing at level 2 and level 3 with a body mass index (BMI) of 22.2 ± 1.6 kg/m^2. 78% of the players participating in this study had previous experience with half-squat strength training.

Paper II study participants

Two female football teams from Norway were randomized to either training (TG) or control groups (CG). The training group consisted of n=24 players with a BMI of 22.1 ± 2.1 kg/m^2 from level 2, where 86% of the players reported to have experience with half-squat strength training. The control group consisted of n=22 players with a BMI of 22.3 ± 3.0 kg/m^2

competing at level 3, where 64% of the players had previous experience with half-squat strength training.

Paper III study participants

Forty-nine (n=49) male football players with a BMI of 24.5 ± 2.0 kg/m^2 playing at level 5 and 6 in Norway participated in this study. Average weekly resistance training volume was 2.6 ± 1.8 hours.

Paper IV study participants

Nine (n=9) female football players with a BMI of 21.7 ± 1.0 kg/m^2 playing for a Norwegian team at level 3 participated in this study. All the players had previous experience with half-squat strength training.

***Table 1**: Characteristics of study participants.*

	Sex	*n*	Age (years)	Body mass (kg)	Performance level
Study I	Female	37	18 ± 2	62 ± 5	Level 2-3
Study II	Female	46	18 ± 3	63 ± 8	Level 2-3
Study III	Male	38	24 ± 3	80 ± 9	Level 5-6
Study IV	Female	9	19 ± 2	61 ± 4	Level 3

Age and body mass are stated as mean ± SD

Methods and characteristics for supplementary analysis

Supplementary analysis I and II

A training match was played within each group before and after the training intervention in *paper II*. Playing time, and tracking of physical match play performance were done according to the methods described in *paper I*. Of all players that were selected for pre- to post-test analysis in *paper II,* eight players in the training group and seven players in the control group completed 90 minutes of playing time in the same position. For *supplementary analysis II*, baseline strength of players proceeding from pre-post analysis in the TG of *paper II* were compared with players in the barbell free weight group from *paper III.*

Table 2: *Characteristics of the players in supplementary analysis I*

Group	Sex	*n*	Age (years)	Body mass (kg)	Height (cm)
TG	Female	8	17 ± 1	62 ± 6	165 ± 6
CG	Female	7	19 ± 2	59 ± 6	159 ± 6

Age, body mass, and height are stated as mean ± SD. TG; training group, CG; control group.

Table 3: *Characteristics of the players in supplementary analysis II*

Group	Sex	*n*	Age (years)	Body mass (kg)	Height (cm)
TG	Female	19	18 ± 3	62 ± 5	167 ± 6
TG	Male	13	23 ± 2	79 ± 12	181 ± 0.1

Age, body mass, and height are stated as mean ± SD. TG; training group

3.3 Procedures and equipment

Technical equipment used in this thesis is described in Table 4.

Assessment of strength

Half-squat 1RM was directly assessed by applying single repetition trials with increasing loads of 5–10 kg until the players were unsuccessful in an 1RM attempt. The trials were interspersed by minimum three minutes of rest. In line with previous research, the 90° angle between femur and tibia were controlled by visual inspection (65, 70, 99, 129) and the aid of a goniometer (98) (Figure 1). Half-squat strength 1RM assessment is reported to have a high test-retest reliability with an intra class correlation (ICC) of 0.97 for females (130).

Figure 2: The author visually confirming the anatomical correct position for the half-squat with a goniometer, with a 90° angle between femur and tibia being present for the participant.

Assessment of sprint times

Sprint times from tests over 15 m (*paper I*, *II* and *IV*) and 10 m (*paper III*) were measured inside on a dedicated running track with synthetic grass surface. Single-beam photocells (ATU-X, IC Control AB, Stockholm, Sweden), attached to the floor and walls recorded the sprint times. The first photocell at the starting line was positioned 20 cm above the ground, while photocells at 5 m, 10 m and 15 m were placed at a height of 100 cm. In all papers within this thesis, players attempted three sprints with a minimum of three minutes recovery. Sprint time reliability using photocells is reported for males for 10 m sprint, where a ICC of 0.91 (131), and coefficient of variation (CV)s of 1.5-1.8% are evident (131, 132). For 5 m split times, the precision is lower, with a ICC of 0.82, and a CV of 4.4% (133). The distance from the starting point to the first timing gate was 30 cm. This was chosen because the distance from start to the initial timing gate has been reported to affect sprint time when 30 cm was compared with 50 cm and 100 cm (134). However, there is no differences in the initial timing gate error between these distances, and as such 30 cm has been recommended (134).

Assessment of jump ability

Counter movement jump was used to determine jump height in *papers I, II*, and *III*, as well as additional force variables included in *paper IV*. A portable force platform (FP 4; HUR Labs Oy, Kokkola, Finland) was used for the assessment of CMJ height, which is in line with previous literature (121). The force platform sampled at a rate of 1200 Hz. Players were required to bend their knees to approximately 90° and then rebound upward in a maximal vertical jump. The included players performed two CMJ attempts (except for *paper III*, where three attempts were given) with three minutes of recovery between each attempt. CMJ has a ICC of 0.98 for female football players (118), and with a CV of 3% (73).

Assessment of physical match play performance

All matches in this thesis were played during pre-season at Alfheim Stadium in Tromsø, Norway. Physical match play performance was monitored using a stationary radio-based tracking system capturing positional data at 20 Hz (ZXY Sport Tracking AS, Trondheim, Norway) as described elsewhere (135, 136). Each player wore a belt around their waist, with sensor tags placed on the middle of the lower back. Tracking was started and stopped from a computer by the author during all investigations. All matches consisted of 2 x 45 min play interspersed by 15 min half time breaks. The participating teams were instructed to warm-up according to their normal match routines. In general, local positioning tracking systems are shown to have a coefficient of variation of around 1.6% (137), where distance travelled is in the range of 1-1.6% CV. This is more precise than the reported 4.8% on average for video tracking, and 5.8% on average for GPS (135, 137). High intensity runs have been found to have a CV of 3.1% with the ZXY local positioning measurement system, compared with 37.4% for a GPS device, when measured in our lab previously (135). The cut-offs applied for speed zones, acceleration, and deceleration can be found in *paper I*.

Measurement of body composition

Each subject underwent one total body DXA scan (Lunar Prodigy; GE Medical Systems, Buckinghamshire, UK). The scanner was calibrated each morning using a phantom calibration item, following the manufactures instruction. Analysis used encore pediatric software. Precision for total body composition measures is reported to be 0.8% for lean body mass and 2.7% for fat mass with this device (138). The test was carried out by a trained research assistant at the participant’s first visit to the lab in the afternoon between 18:00-20:00. Subjects wore sports underwear, and all jewelry and metal were removed prior to the scan.

Questionnaire

In *paper IV* a questionnaire was made to capture the players perception of their training habits during the COVID-19 lockdown. Before constructing the questionnaires, specific objectives were addressed (139). Specific objectives of the questionnaire were to retrospectively compare: (1) perceived adherence to training; (2) quality of training; and (3) motivation towards training for the periods before and during the lockdown in the pre-season of 2020. The questionnaire was designed with scaled item closed questions, where the relative frequency of behavior was referred to. This follows the Likert-type method where the intervals between responses are thought to be equal (139). Two months after the post-test in June 2020, the players received an individual digital custom-made questionnaire about their pre-season training habits before and during the lockdown. This consisted of six questions in a bipolar five-unit and three-unit Likert-scale. The first three questions referred to the pre-season period prior to the lockdown, while the later three questions were focused on the period during the lockdown. The questionnaire was designed by two sports scientists, and later reviewed by and additional two sports scientists, where the final version was developed with consensus from all four researchers according to the recommendations of Thomas *et al.* (139).

Table 4: *Materials and equipment used in the studies*

Study	Type of equipment	Model and manufacturer
I, II, III, IV	Timing gates (single beam electronic barriers) mounted	ATU-X, IC control AB, Stockholm, Sweden
I, II, III, IV	Portable force platform	Hur-Labs, ALU4, Finland
I, II, III, IV	Olympic Barbell	T-100G; Eleiko, Halmstad, Sweden
III	Flywheel squat apparatus	#215 YoYo Squat Unlimited Pro, nHance, YOYO Technology, Stockholm, Sweden
I, *Supplementary analysis I*	Wearable microtechnology for tracking of movement (Local positioning measurement)	ZXY Sport Tracking AS, Trondheim, Norway
IV	Body composition (Dual-energy x-ray absorptiometry)	Lunar Prodigy; GE Medical Systems, Buckinghamshire, United Kingdom

3.4 Statistical analyses

In all papers, normality distribution was examined with visual inspection of Q-Q plots together with the Shapiro-Wilk normality test. All values are presented as mean ± standard deviation (SD) unless otherwise stated.

Paper I

Pearson's correlation coefficients (*r*) (Spearman´s rho (*ρ*) for non-normally distributed variables) were used to assess the association between physical match play performance (total distance, high intensity running distance, sprint distance, acceleration counts, decelerations counts, and peak match speed) and laboratory-based assessments, as well as between the different laboratory tests. A Pearson's correlation coefficient of ≥0.1 was considered small, ≥0.3 moderate, and ≥0.5 large (140). In the paper it is stated that the effect sizes are the same as for Pearson's *r*, but this is not applied in the results or discussion. To test for significance of the difference between two correlation coefficients (*i.e.*, central vs. lateral positions on the same variables), the Fisher r-to-z transformation was used. Additionally, the Benjamini

Hochberg method was applied to decrease the false discovery rate for the *P*-values of repeated measures (141).

Paper II

Data was analyzed via a two x two repeated measure analysis of variance (ANOVA). Two levels corresponding to the groups (*i.e.*, TG and CG) were specified as the between-subjects factor. The within-subjects factor (time of test) represented the pre- and post-tests. Effect sizes were calculated as partial eta squared ($p\eta^2$), where small, medium and large effect sizes was determined as 0.01-0.05, 0.06-0.13, and ≥ 0.14, respectively (142).

Paper III

We performed paired sample t-tests to assess pre- to post-test changes within groups. One-way univariate AVOVAs with Bonferroni corrected post-hoc tests were used to examine differences in baseline characteristics, and in the change score from pre-to post-test between the groups. Effect sizes were calculated as Cohen's d, where determination of magnitude was considered according to Rhea's recommendations (143). For pre- to post effect size within groups, we divided the mean change score by the standard deviation (SD) of the change score. We calculated between groups effect size by the pooled SD of the two groups of interest (*i.e.*, flywheel training group (FW) vs barbell free weight training group (BFW), FW vs CG, BFW vs CG) divided by the difference in mean change score of the two groups of interest. We used Pearson's correlations to assess the association between the change in sprint time and jump height, respectively, and the change in maximal half-squat strength. We adopted linear regressions to assess whether inclusion of changes in body mass could explain more of the variation in the association than maximal halt squat change alone (144, 145).

Supplementary analysis I

Within group changes from pre-to post-test were analyzed using paired sample t-tests. For changes between groups from pre- to post-test, independent sample t-tests were done on the pre- to post-test change for each variable between each group.

Supplementary analysis II

This analysis was performed on data from *paper II* and *paper III*. An independent t-test was performed on baseline strength for the barbell free-weight male training group in *paper III* against the female training group in *paper II*.

Paper IV

For 1RM, CMJ, and 15 m sprint times we used Student paired sample t-tests to determine the change from pre- to post-test. For training and questionnaire data, non-parametric tests were used for analyses as these variables were non-normally distributed. For the questionnaire data (*i.e*., training adherence, quality, and motivation), we used a non-parametric sign test to assess the direction of the data from pre-post lockdown (146).

All papers and additional analysis were performed using the Statistical Package for Social Sciences (SPSS, Version 25 (for *paper I*), 26 (for *paper II, paper III paper IV,* and *supplementary analysis I* and *II*), IBM, USA). Additionally, R Studios (R core team, 2021) were used for analysis in *paper I.* Alpha level was set to 0.05 for level of statistical significance in all papers. For more detailed information about each study's statistics, please refer to the distinctive papers.

4 Results

4.1 Paper I: Associations between maximal strength, sprint and jump height and match physical performance in high-level female football players.

The aim of this study was to assess the association between 1) 1RM, 2) 5-, 10- and 15 m sprint, and 3) CMJ, and physical match play performance assessed as total distance covered, running distance, high intensity running distance, sprinting distance as well as acceleration and deceleration counts, and peak speed in high-level female football players.

We found no significant correlation between 1RM half-squat strength and physical match play performance. There was a strong correlation between 10 m, 15 m sprint time ($r = -0.56$, $r = -0.56$, $P < 0.001$), and CMJ jump height ($r = 0.50$, $P < 0.01$) with peak match speed. Further, there was a moderate correlation between 15 m sprint time and acceleration count ($r = -0.43$, $P < 0.05$). 5 m sprint time did not correlate with physical match play performance. There were no differences in correlations between playing positions for any of the variables (all $P > 0.05$).

In conclusion, tests of 10 m and 15 m sprint time, but not maximal strength in half-squat, were significantly associated with measures of high intensity physical match play performance. Counter movement jump height was also significantly associated with peak match running speed.

4.2 Paper II: Improved maximal strength is not associated with improvements in sprint time or jump height in high-level female football players: a cluster-randomized controlled trial

The aim of this study was to examine if maximal strength training (MST) improved maximal strength, and if so, did the strength gain result in superior sprint and jump height performance in high-level female football players.

We found no main effect of time for 5 m ($P > 0.05$, pη2 = 0.003), 10 m ($P > 0.05$, pη2 = 0.002) or 15 m ($P > 0.05$, pη2 = 0.026) sprint time, and consequently no interaction effects of time x group was observed (5 m: $P > 0.05$, pη2 = 0.097, 10 m: $P > 0.05$, pη2 = 0.003, 15: $P > 0.05$, pη2 = 0.014) from pre to post intervention. Similarly, no main effect of time for CMJ was observed ($P > 0.05$, pη2 = 0.001), and consequently no interaction effect of time x group ($P > 0.05$, pη2 = 0.006). The players increased their 1RM in half-squats (main of effect of time: $P < 0.001$, pη2 = 0.704), and an interaction effect of time x group was observed ($P < 0.00$, pη2 = 0.516) where the TG increased their 1RM significantly more (31 kg) than the CT (6 kg) (between subjects' effect: $P < 0.001$, pη2 = 0.965).

We concluded that the improved 1RM following MST was not associated with improvements in sprint or jump height performance.

4.3 Supplementary analysis I

The aim of *supplementary analysis I* on a subsample from *paper II* was to investigate the change in physical match play performance from pre to post intervention.

Eight players in the training group and seven players in the CG completed both the pre and post intervention match. Only the TG increased maximal strength ($P < 0.05$) from pre-to post intervention, and the change was larger compared to the control group ($P < 0.01$) (Table 5). The training group decreased high intensity running distance ($P < 0.05$), and total distance ($P < 0.05$) from pre to post intervention. Both high-intensity running distance ($P < 0.05$) and sprinting distance ($P < 0.05$) increased in the CG from pre to post intervention ($P < 0.01$), being significantly different from the change in the TG ($P < 0.05$).

We concluded that increased maximal strength following MST did not improve physical match play performance in female football players.

Table 5: Match and laboratory variables for TG and CG for pre- and post-test.

	TG (n=8)			**CG (n=7)**			
	Pre	Post	*P*-value*	Pre	Post	*P*-value*	*P*-value**
Body mass (kg)	61.7 ± 5.7	62.4 ± 5.5	0.019	59.4 ± 5.8	60.2 ± 5.2	0.297	0.833
15 m sprint							
5 m time (s)	1.06 ± 0.05	1.05 ± 0.05	0.413	1.06 ± 0.05	1.07 ± 0.02	0.489	0.288
10 m time (s)	1.90 ± 0.06	1.89 ± 0.09	0.588	1.92 ± 0.08	1.90 ± 0.06	0.475	0.804
15 m time (s)	2.65 ± 0.10	2.64 ± 0.13	0.272	2.68 ± 0.11	2.67 ± 0.09	0.245	0.914
CMJ height (cm)	27.2 ± 6.4	26.7 ± 6.4	0.207	25.6 ± 4.3	26.3 ± 4.0	0.580	0.325
1RM 90° squat							
kg[1]	106 ± 22	142 ± 18	<0.001	106 ± 12	114 ± 19	0.140	<0.001
kg/mb kg^{-1}	1.73 ± 0.36	2.29 ± 0.36	0.002	1.80 ± 0.25	1.90 ± 0.36	0.040	0.001
$kg/mb^{-0.67}$	6.73 ± 8.93	8.93 ± 1.24	0.002	6.92 ± 0.87	7.32 ± 1.30	0.041	<0.001
TD (m)	9609 ± 815	9243 ± 586	0.034	10077 ± 680	10076 ± 1320	0.998	0.396
HIR (m)	957 ± 329	794 ± 325	0.025	892 ± 453	1211 ± 523	0.014	0.001
Sprinting (m)	248 ± 116	254 ± 162	0.909	189 ± 162	357 ± 252	0.028	0.046
ACC (counts)	33 ± 23	33 ± 17	0.988	44 ± 37	32 ± 18	0.435	0.456
Peak speed ($km \cdot h^{-1}$)	24.93 ± 1.14	25.24 ± 2.38	0.669	24.14 ± 2.00	24.78 ± 1.68	0.083	0.685

Data are shown as mean ± SD. TD, total distance; HIR, high intensity running distance; ACC, acceleration counts; DEC, deceleration counts; CMJ, counter movement jump; 1RM, 1 repetition maximum. Physical match play variable cut-offs can be found in *paper I,* **P*-values within groups are based on paired sample t-test; ** *P*-value between groups are based on independent sample t-test on the pre-post change for each group.

4.4 Paper III: Flywheel squats versus free weight high load squats for improving high velocity movements in football. A randomized controlled trial.

The aim of this study was to compare the effect of flywheel resistance half-squat training vs barbell free weight resistance half-squat training on maximal dynamic strength, sprint time and jump height in male recreationally active football players.

We observed differences in changes in the 10 m sprint test between the groups (between subjects effect: $P < 0.001$), where the FW and the BFW group equally decreased their 10 m sprinting time from pre- to post-test by 2% (between groups: $P > 0.05$, Cohen's d: 0.00, pre- to post-test: FW group: $P < 0.001$, Cohen's d: − 0.97; BFW group: $P < 0.05$, Cohen's d: − 0.96), while the CG did not decrease their sprinting time ($P > 0.05$, Cohen's d: 0.26; difference between FW and BFW vs CG: both $P < 0.001$, both Cohen's d: − 1.39).

There were differences in changes in the CMJ test between the groups (between subjects effect: $P < 0.001$), where the FW and the BFW group equally increased their jump height in the CMJ test from pre- to post-test by 9 and 8%, respectively (between groups: $P > 0.05$, Cohen's d: − 0.16; pre-to post-test: FW: $P < 0.001$, Cohen's d: 1.70; BFW: $P < 0.001$, Cohen's d: 1.54), while the CG did not increase their jump height ($P > 0.05$, Cohen's d: 0.09; difference between FW and BFW vs CG: both $P < 0.001$, Cohen's d: FW vs CG: 2.15, BFW vs CG: 1.94).

There were differences in changes in the 1RM half-squat test between the groups (between subject effect: $P < 0.001$), where the BFW group increased their 1RM half-squat by 46%, which is more than the FW group's increase of 17% (difference between groups: $P < 0.001$, Cohen's d: 3.43, pre- to post-test: FW: $P < 0.01$, Cohen's d: 3.13, BFW: $P < 0.001$, Cohen's d: 3.17), and the BFW and the FW group increased their 1RM half-squat more than the CG (difference between FW and BFW vs CG: both $P < 0.001$, Cohen´s d: FW vs CG: 2.71, BFW vs CG: 4.93, pre-to post-test CG: $P > 0.05$, Cohen's d: 0.51). When scaling 1RM half-squat strength to the power of 0.67, the results remained unchanged.

We concluded that half-squat resistance training carried out either with flywheel device or barbell free weight are equally effective at improving sprint time and jump height in male football players. However, the barbell free weight training group experienced a more than two-fold larger increase in maximal barbell free weight half-squat strength.

4.5 Supplementary analysis II

The aim of this analysis was to compare baseline strength levels between male and female football players undergoing MST.

Relative strength was not different between the male and female football players (0.02 kg/ m_b kg^{-1}, $P > 0.05$), which was also shown for scaled strength (0.44 kg/$m_b^{-0.67}$, $P > 0.05$) (Table 6).

We concluded that baseline relative and scaled maximal strength was not different between males and females performing MST in the thesis.

Table 6: Comparison between *paper II* and *III* for baseline differences.

	Male MST group n=13	Female MST group n=19	Between group difference (%)	*P*-value
Body mass (kg)	78.9 ± 12.0	61.7 ± 5.4	24.5	< 0.0001
Half-squat (90°)				
1RM (kg)	134.6 ± 27.0	106.3 ± 21.0	23.5	0.002
1RM (kg/ m_b kg^{-1})	1.71 ± 0.24	1.73 ± 0.33	1.2	0.84
1RM (kg/$m_b^{-0.67}$)	6.96 ± 1.06	6.52 ± 1.23	6.5	0.30

MST; maximal strength training, P-value represent the probability value from an independent sample t-test between the male MST group and female MST group.

4.6 Paper IV: Maximal strength, sprint and jump performance in high-level female football players are maintained with a customized training program during the COVID-19 lockdown.

The aim of this study was to investigate the effects of unsupervised 12-week home- and group- based training without gym facilities on maximal strength, CMJ height, and 15 m sprint time in female football players during the COVID-19 lockdown.

We found no significant changes for absolute- or relative 1RM half-squat strength ($P > 0.05$), CMJ height ($P > 0.05$), force production variables in the CMJ test (all $P > 0.05$), or in 15 m sprint times ($P > 0.05$, in all cases) from pre- to post-test.

In conclusion, maximal half-squat strength, CMJ, and sprint performance were preserved in female football players during a 12-week period of unsupervised training without access to gym facilities during the COVID-19-induced lockdown.

5. Discussion

5.1 Methodological considerations

To expect an experiment to meet all research design criteria is unreasonable (139). Specifically, a researcher has to balance the emphasis put on either internal or external validity in order to produce high-quality relevant research (139).

Internal validity

Internal validity can be considered the true association between exposure and outcome (147). Ensuring internal validity involves controlling all variables and excluding all rival hypotheses as explanations for the observed outcomes (139). This is done by maximizing the reliability and the accuracy of the study's results, and by minimizing bias (147).

Instrumentation

Performance tests of strength, jump height and sprint were carried out in *paper I, II, III* and *IV*. Standardization of instrumentation, or lack thereof, during such testing may severely impact the internal validity. Instrumentation concerns apparatus, testing equipment and observers (148). Validity of the tests applied in this thesis are further detailed in the methods section, or in the respective papers. Several factors have the potential to affect performance testing and should therefore be controlled and considered to ensure high internal validity. For example, verbal encouragement during testing could affect the athlete's response, and thus the test result. In this context, one particular detail to be aware of is to standardize the volume and the pitch of the voice during all tests if using verbal feedback to motivate the athlete prior to or during the test phase (149). Another aspect is to direct the attention towards an external focus instead of an internal (150). In all our strength tests a typical phrase such as "push the bar hard towards the roof" was repeatedly used, instead of phrases with an internal focus, like for example emphasizing body parts or the muscles utilized. Importantly, the external attention was used for all tests in this thesis. It is well established that monitoring of sprint times over short distances (10-20 m) may vary considerably (151). Nevertheless, the single-beam photocells used in this thesis were mounted to the inside walls of the laboratory, reducing error in placement of the cells, and negating the potential confounding effects of environmental and surface factors.

Testing

Testing is also a threat to internal validity, where the effect of one test can affect a subsequent test (139). In *paper I, II, III* and *IV*, jump and sprint testing preceded all strength testing since strength exercise has been shown to affect subsequent sprint and jump performance in both males and females (152). A recovery period of at least >48 hours were provided after strength testing and match play in *paper I* and *supplemental analysis I*, to avoid any comprises in muscle function (153). Familiarization with a testing procedure may also improve subsequent test results (148), and so all players were familiarized with the half squat exercise for *papers I, II* and *IV*. One potential solution is to test the 'effect of testing'. Häkkinen, Newton, Gordon *et al.* (154) elegantly showed this by commencing a strength training study with three weeks of control period, before a 10-week strength training intervention. Their outcome variables remained unchanged during these three weeks, suggesting little effect of testing.

History

History could be a threat to internal validity because an event outside the treatment could potentially affect the outcome of the experiment. In *paper II*, the randomization to treatment was based on clusters of two already existing teams. Thus, the difference in training approaches within each team's football training introduce a threat to the internal validity because other components than the treatment is likely to benefit the outcome variables. In *paper III*, players were randomized to different treatment or control groups across multiple teams, which methodologically controls for history.

Experimental mortality

The loss of participants can affect internal validity and can occur regardless of randomization (139). For example, treatments could be perceived as too time consuming and lead to drop out. When researching high-level athletes, dropouts are normal and expected (155). Especially when working with nonprofessional athletes who are often time-poor and must balance a high training load to reach their goals (*e.g.,* become professional) with studies or work. This applies to all athletes in this thesis, who were all are non-professional football players. Conducting studies with full time professionals might be expected to reduce the high dropout rate seen in part-time professionals and amateurs (156). Moreover, it is suggested that data collection should be minimized to few days and undertaken immediately right prior to, and after, the intervention period to reduce drop out (156). On the other hand, a potential delayed effect of strength training on explosive performance is a valid argument for including some days between ended intervention and retesting (157).

Statistical regression

Statistical regression may occur when groups are formed based on extreme values of measurement, and consequently move towards the mean (148). In *paper II*, the two team clusters played at two different competitive levels, which could have led to dissimilar measurements in the two groups at baseline (>2 % difference in 1RM (kg/ m_b kg^{-1}), P= 0.084).

Selection bias

Bias is any tendency which prevents unprejudiced consideration of a research question (147). Selection bias arise from any error in the process when selecting participants for inclusion in a study, and from factors influencing the participation (158). Research in sports science consistently include elite or highly trained participants to study special characteristics related to performance (159). This is suggested to increase the issue of endogenous selection bias (159). For all studies in the thesis, athletes and teams are especially invited to participate based on some selected characteristics. However, selection bias occur when criteria used to recruit participants into distinct cohorts differs between the groups (147). Prospective studies, such as *paper II* and *paper III,* rely on randomization when the outcome is still unknown, and are therefore less susceptible to selection bias (147). However, in *paper II*, the players were randomized from two clusters (teams) to either treatment or control. Importantly, just showing that the groups were similar on the outcome variable at pre-tests does not eliminate selection bias, because another unmeasured variable potentially could influence the outcome (139). In *paper I*, an effort was made to explain the different sample sizes seen between correlation analyses. Especially where tests are insufficient for some players, this is described. Earlier, studies that did not explain changes in sample sizes have been criticized and made susceptible to selection bias (155).

Expectancy

Expectancy relates to researchers or test administrators belief that study participants will perform or behave in a certain way (139). This is usually not a deliberate choice made by the researcher. If the experimental and control groups are identified, observers may rate the experimental group better. In drug testing research, a common method is double blinded studies, where neither the administrating researcher nor the participant know whether a drug or a placebo is given. A potential solution to minimize expectancy in performance testing research is the use of single blinded studies, where the test administrator does not know whether the participant is in the training or the control group. Due to resources and feasibility, this was not done in the studies for this thesis.

Logical validity, criterion validity, and construct validity

Logical validity is established when a measure involves the performance being measured (139). For example, acceleration can be assessed by running an all-out test between two timing gates with a distance of 15 m. Criterion validity addresses to which extent a test measure is related to a criterion test (139). In contrast to logical validity this is done objectively (160). The criterion validity of tests illustrates their ability to make interpretation for a criterion measure of performance in competitive conditions (78). Often, when a gold standard measure is available, criterion validity reflects how the measure of interest relates to the gold standard (161). Criterion validity for the measurements used is described when available in each consecutive paper. Construct validity of a test can be measured by comparing groups of different abilities (160). If the test chosen can discriminate the two groups, it holds good construct validity. Construct validity of the laboratory tests and physical match play performance variables applied in this thesis are described in the introduction chapter. Further, construct validity can be established by means of correlation (139). For example, in *paper I*, we tested the association between high intensity running distance and maximal strength using correlation analyses.

Measurement bias

It is well established that in sports such as football, many variables interact in a complex manner and may affect the outcome (162). Reliability for physical match play performance is low for female football players (36). Therefore, the findings in *supplementary material II* should be interpreted with caution, as a plethora of uncontrollable factors make it difficult to detect changes in physical match play performance in football due to a training intervention (160).

Eternal validity (generalizability)

External validity is the ability to generalize results to other participants and settings outside the study (139). Often research emphasize internal validity. In an applied discipline, as with sports science, external validity needs to be emphasized (163). There are several threats to external validity (148).

Reactive/ interactive effects of testing

Pretest may impact a post-test, because it could make participants more aware of the current state of fitness at the time of the pretest (139). This may apply to both *paper II, paper III,* and *paper IV.* In *paper II*, a significant improvement of 5% in 1RM were observed in the CG, which may be attributed to this effect, as they were not given any treatment. Another explanation of this finding could be the Avis effect, which occurs when participants in control groups try harder for the reason that they are in the control group (139).

Interaction of selection bias and the experimental treatment

The interaction of selection bias with the intervention may diminish the ability to generalize the results to participants with other characteristics (139). For example, the training of high-level female football players in *paper II* may not allow for direct interpretations to players of professional status. The training conducted in this study may lead to lower gains in strength in players of a higher training status, as they are more likely to have more time devoted to training, and more resources available in their everyday training. On the other hand, professional level players may experience greater effects of the same training program as well, as they probably have more time and resources available for recovery.

Reactive effects of experimental arrangements and ecological validity

In sports science, researchers have been criticized for failing to produce and disseminate findings applicable to practical settings (164). The reactive effects of interventions imply that they may not relate to real world scenarios (139). Often reactive effects that occur if laboratory-based outcomes fail to be generalizable to settings outside the laboratory. It has been advocated that more research on sports science should be carried out in the field (139). In football, this could be physical match play performance (78, 160). Thus, ecological validity of a test is evaluated by its association with physical match play performance (165). In this thesis, ecological validity is established in *paper I*. To minimize the reactive effects of interventions, both outcomes of high internal validity measured in laboratory settings are included in *paper II* and *II*, as well as real world physical match play performance in *supplementary analysis I*.

Multiple-treatment interference

In *paper II* and *III,* the exposure variables (maximal half-squat strength training / fly wheel training) were balanced with the Nordic hamstring exercise, an evidence-based injury preventive strength training stimulus for the hamstrings (166, 167). This was done as an ethical sound consideration based on previous results, but may negatively influence the internal validity, as two exposure exercises are utilized instead of one. Nevertheless, the author supports the idea that sports science should, as stated by Damian Farrow in a roundtable discussion, "*be concerned with sport and its athletes"* (168), and therefore proper injury management should be incorporated. Hamstring/quadriceps strength ratio is a proposed injury risk factor (169). By only emphasizing knee extension exercises, an elevated imbalance reflected in this ratio may occur. Thus, we included the Nordic hamstring exercise to improve knee flexion strength in that study, and in turn to anatomically balance the strength training, with a sound stimulus on both the agonist and antagonist. The author acknowledges that a multiple-treatment interference effect may be present, and that the ability to generalize the findings may be confounded by the use of two exercises in the treatment (139). A better solution would have been to also include the Nordic hamstring exercise in the control groups. For example, the Hawthorne effect may introduce an reactive effect in a trial, because attention from the researchers are directed towards the participants (139). It may well be that such effects were present in both *paper II* and *paper III*, where more attention were given to the intervention groups than to the control groups that did not receive a placebo. It is practical and methodological difficult to administer a placebo to a training intervention, and is more applicable to, for example, nutritional interventions, where blinding and double-blinding can be used to minimize the Hawthorne effect (139).

Generalization

The female players included in this thesis for *paper I*, II and *IV* are defined as "high level" according to the definitions of Okholm Kryger, Wang, Mehta *et al.* (170), and the findings may not be transferrable to other athletic performance levels. Existing studies on the physical demands of football have mainly focused on professional and international level players (171). Interestingly, the female football teams with the best results in the 2012 Olympic games showed the highest average age in the tournament (>26 years), while the teams that failed to qualify for the quarter-finals were younger (~22 years) (172). Similar outcomes were observed in the underlying physiological capacities as well, with players <20 years found to have poorer sprint time than players in the category 20-24 years and >24 years (80). The cohorts of players in this thesis were young (mean age 18.5 years) and do not represent the potential peak age of female football players (172). However, our results provide an insight into the requirements across all competitive levels and a more comprehensive understanding of the physical readiness for the demands of the sport, as well as from a player development perspective (171). The low number of matches played in *paper I* are too limited to represent a football season (173) and so should be interpreted cautiously. A problem of standardized cut-offs for physical match play performance has produced the call for more stringent methods, in order to produce a comparable body of research (173). The most commonly used definitions for high intensity running distance and sprinting distance in the female football literature, >16 $km \cdot h^{-1}$, and >20 $km \cdot h^{-1}$ (6), were applied in *paper I* and *supplementary analysis I.*

The goal of experimental research is to establish cause-and-effect relations (139). Although they have proposed a methodological construct between *paper II* and *paper III*, the author acknowledges that the methods and protocols were not identical. Even though both studies had 5 weeks of MST within the terminology proposed by Heggelund *et al.* (95), there was a deviation in the details such as repetitions and training sets.

5.2 Discussion of results

This thesis provides novel findings on the ecological validity of maximal strength for football match play, the effects of MST, and how a period without systematic MST influence maximal strength and high force – high velocity actions in female football players. The main findings were:

1. Maximal strength (1RM) was not associated with physical match play performance in female football players, whereas sprint performance and jump height were strongly correlated.
2. MST in female football players led to improved maximal strength; however, there was not a concomitant improvement in jump or sprint ability. Physical match play performance did not improve and instead was found to deteriorate for high intensity running distance in a sub-sample from the training group from pre-to post intervention. For sprint distance and high intensity running distance, a sub-sample from the control group increased from pre-to post intervention, being significantly different from the change in the training group.

3. Unlike female, MST in males led to improved jump and sprint ability, despite the training being performed in the same lab, with the same equipment, and starting at the same relative and scaled maximal strength level as the female players in *paper II*.
4. During a period of restricted access to training facilities and organized MST female football players did not change their maximal strength, sprint times, nor jump height.

5.2.1 Strength associations

In *paper I*, no significant correlation was found between maximal strength and physical match play performance. Earlier, investigations have shown that training status and a variety of fitness tests are related to physical match play performance in males (57), and in females (56). One of the main purposes of assessing maximal strength is to quantify the relative importance it has to athletic tasks (68). Strength is considered a base component of sports performance, being connected to explosive actions such as sprint and jump performance (65). The logical validity of strength and rapid force production are manifested in football through observations like sprints and jumps being connected to goal scoring situations (41), and the notion that duels, kicking and heading requires strength and power (62, 70, 91, 174). Moreover, explosive actions like change of direction are shown to induce peak forces >3 times body weight on female football players (175), indicating the importance of strength and power in football.

Further, construct validity for strength in football is established for football players of both sexes. For males, Wisløff *et al.* (70) observed that the 1RM half-squat strength of the league winning team was higher than for the poorest team. A similar relationship has been observed for isokinetic strength when comparing French male players from the top league with the second league and with amateurs (62). For females, the picture is less clear. Although Manson *et al.* (69) found isokinetic strength differences between starters and non-starting international level players, no differences were observed between regional and international players in England (71).

During the last two decades it has been observed that strength training, and enhancement of strength and power abilities are associated with improved short- and long-term endurance performance (176). Therefore, strength may play a role for physical match play performance through its relationship with movement economy. Football match play mostly relies on aerobic energy production (177). Since work economy is the aerobic energy cost required to perform submaximal game-specific tasks, it could be speculated that players with a better work economy use less energy to perform the movements required throughout a game and, thus, preserve energy for important high-intensity actions (178). For example, VO_{2max} is found to be highly (r = 0.81) correlated with high intensity runs in female football players (56), demonstrating the importance of oxidative metabolism in female football players. It appears that increased maximal strength corresponds with improved work economy in male football players (99), which theoretically suggests that players are able to do more external work for the same aerobic cost. Further, maximal strength may be important for repeated intermittent high intensity exercise, as maximal strength has been previously found to relate to performance during intermittent all out efforts (179). Previously, absolute strength has been hypothesized to be important in duels and when force is transmitted to external objects (*e.g.* the ball, or competing for possession) (91).

However, relative strength is proposed to be important for high force activities such as sprinting, accelerations and decelerations (91). Previously, a study in male football players demonstrated that isokinetic strength was associated with an ability to resist temporarily fatigue during match play (72). In this study, the correlations were based on differences between 15-minute playing intervals during match play, and with different tracking technology, thus, caution should be made when compared this study with our findings in *paper I*. To date, research utilizes numerous different tracking systems for locomotor categorization, and a wide set of cut-offs for different speed zones has been applied (6). Comparing absolute values between different systems are not recommended due to their inherent differences (180). This holds not just between systems (*e.g.*, LPS, GPS), but also within systems (5 Hz vs 10 Hz) (181). Nevertheless, their study identified a strong association between strength and match play, whereas our study did not. Considerations should also be made when interpreting type of strength. The results found in this thesis on dynamic strength may not apply to strength measured in other forms. For example, although two months of dynamic strength training was shown to increase dynamic 1RM by 67%, isometric strength only improved by 13% (182). Furthermore, following dynamic strength training, changes in isometric and dynamic strength were not found to be correlated (183).

The earlier observed association between isometric strength and physical performance during small-sided games (184), and the associations between isokinetic strength and the ability to resist physical match play performance decrements over the course of a game (72) favours greater strength levels. However, they may differ from the findings in *paper I* due to the different methods of strength assessment, or different sexes included.

The relationship between strength and explosive characteristics, such as jump height and sprint speed, has been shown for male football players when using similar methods to those used in the present thesis (65). Nevertheless, in *paper I,* there were no significant correlations between maximal strength and peak speed in match play performance, as well as no significant correlation between maximal strength and 5 m, 10 m or 15 m sprint times, despite previous literature that have either used the same methods (90° half-squat 1RM) (65), and having found an association between strength and sprint speed (61, 185). However, our finding do align with a recent study in elite female football players, demonstrating that 1RM estimated from force velocity profiling from the jump squat correlated poorly with 10 m sprint time, where only a small non-significant correlation was found when 1RM was expressed relative to body weight (186).

Additional, moderate correlations were found between CMJ height and relative strength (1RM ($kg \cdot m_b^{-1}$)) and between CMJ height and scaled strength (1RM ($kg \cdot m_b^{-0.67}$)), but not for absolute strength, in *paper I.* This, may suggests that there is a higher importance of relative strength for activities carrying the body (91), and leg strength for vertical power compared to an horizontal task (187). Nevertheless, the finding of a non-significant correlation of $r = 0.33$ between absolute strength and CMJ height in *paper I* is lower than the correlations found earlier for male players ($r = 0.78$) (65). In contrast to these comparisons, it has been suggested that correlations between measures of physical fitness and performance in females is often larger compared to males due to the greater heterogeneity in this group (54). As the CV in the study by Wisløff *et al.* (65) was 12.2% for 1RM, and 7% for CMJ height, the variability of the measurements were not higher in the study by Wisløff *et al.* (65) than in *paper I* (14.7% for 1RM, and 13.9% for CMJ height). Thus, heterogeneity in the data may not explain the divergent findings.

It has been previously shown that the proportion of myosin heavy chain II (MHCII) fibers is a predictor of total sprint distance during match play in males (188), and this has been also correlated with maximal strength (189). Therefore, it could suggest a relationship between strength and sprint distance. However, both sprint distance and strength are influenced by several other factors than MHCII/MHCI ratio, which may explain our finding of no correlations (*P* = 0.09). Neither 5 m nor 10 m sprint time was observed to be correlated with field tests of intermittent endurance ability for female football players in a previous study (190), which is consisted with our findings in *paper I.*

Although peak match speed is affected by several contextual factors (*e.g*. position, age), it is related to linear sprint test performance (191). The rationale for a relationship between sprint and strength is described earlier (65). Our findings of a correlation between the sprint test and peak match speed in *paper I* is in line with previous research (76, 191) and in contrast with one study in male youth players (192). This may seem intuitive, but maximal sprint speed is rarely attained during match play; football players reach approximately 92% of the speed attained during a maximal sprint speed test during their fastest sprint in matches (193). This could be due to other parameters (*e.g*., technical, environmental, tactical etc.) affecting physical match play performance, or it can be based on the fact that the majority of sprints in football are less than 10 m (6), being too short to reach maximum speed (194).

5.2.2 Effects of training

Strength training is considered as a fundamental component of the physical preparation for enhancing sports performance (187). A large body of evidence in male football players has shown that increasing strength with minimal hypertrophy is favourable to increasing maximal strength while at the same time avoiding and/or minimizing weight gain. This is best achieved by high loads (95, 97), low volume (195), sufficient between-sets recovery time (2-5 min) (196), and partial range of motion (107), and it is usually named MST (97, 99, 129, 197). These findings were replicated in our lab for male players in *paper III* and for female players in *paper II*, both demonstrating a large improvement in maximal strength following MST.

Improved maximal strength following training has been associated with improved performance after a fatiguing bout of exercise (198, 199), which could apply especially for female players as the sex differences for physical match play performance is more pronounced towards the end of a game (33). Fatigue manifests itself temporarily and towards the end of a game (111, 200), and is recently reported to reduce the ability to perform repeated sprints in female football players (201). The same study observed a 43% reduction in muscle glycogen over the course of a football match (201). Interestingly, Goreham, Green, Ball-Burnett *et al.* (202) observed a lower glycogen and phosphocreatine depletion after an endurance task at a set power output following a heavy strength training intervention, which may suggest that glycogen sparing is an important adaptation to strength training that could potentially aid physical match play performance.

Bogdanis *et al.* (111) observed an increase in peak power output in a 5 sec sprint on a repeated bicycle sprint test following MST and a concomitant improvement in 1RM strength by male football players. They also observed an increase in the YYIE2 test (111) which is considered a valid indicator of endurance capability in football (203). This suggests that MST may delay fatigue following intermittent or anaerobic work. However, this findings should be considered cautiously, as players in the study increased their VO_{2max} simultaneously during the training period (111). Nevertheless, some proposed mechanisms behind improved endurance performance following MST are delayed activation of type II fibers, conversion of type IIX to type IIA fibers and altered muscle-tendon stiffness (204). Further, following an increase in strength levels, each muscle fiber tension at a given absolute intensity will now occur at a lower percentage of its maximal force generating capacity (204).

Interestingly, 5% improvements in work economy after MST has been reported and a concomitant increase of 34% in 1RM for male football players (14), which may suggest an increase in distance covered during a match by approximately 1 km (205). In contrast, our observed change in 1RM (34 % increase) observed together with the change in total distance (~0.4 km decrease) during match play in *supplementary analysis I* did not support an improvement in physical match play performance following MST. Nevertheless, MST is shown to improve exercise economy in female endurance athletes (206), thus, investigating work economy in female football players is warranted.

However, not all strength training studies lead to improved work economy (207) or endurance related performance enhancements, although maximal strength is increased (208). Several studies using short duration (<8 weeks duration), failed to demonstrate improved endurance performance (176), which is consisted with our results in *supplementary analysis I* from a 5-week intervention.

Increased maximal strength of the lower body is generally thought to translate to improved sprint and jump performance (61, 209). However, the role of increased strength and strength training in improving sports performance has also been questioned (210-212), where some studies have failed to improve sprint times following increased leg strength (213, 214). Concurrent improvements in sprint and jump ability following combined football training and MST were only found in *paper III* for males, and not in *paper II* for females. This is a noteworthy and surprising result warranting further investigation.

It has been suggested that the studies that previously did not find a positive transfer from increased maximal strength to improved sprint performance was due to a low strength increase (>10%)(209). However, the 31% increase in 1RM in *paper II* is well above this magnitude, and in fact higher than the 24% and 25% increase in 1RM needed to improve 10 m sprint time and CMJ height by 2- and 6.8%, respectively (61). These findings indicate that a low 1RM increase may not explain the lack of an improvement in sprint and jump performance in *paper II*. Conversely, the male maximal half-squat strength training group in *paper III* increased their 1RM by 46%, with a concomitant improvement in 10 m sprint performance of 2% and an increase in CMJ height of 8%. Although slight differences are evident, these findings are consistent with a single-arm experimental study (*i.e.* no control group) in male Champions League level players, where a 52% increase in 1RM occurred with a concurrent improvement in 10 m sprint time and CMJ height of 3.2% and 5.2%, respectively (99). Thus, *paper III*, but not *paper II* support the typical notion that an increase in squat 1RM transfer more to CMJ than to sprinting (187). Nevertheless, in female football players, this warrants further research.

Further, we did not observe an improved physical match play performance from pre-to post-test in *supplementary analysis I.* Previously, research limited to youth male players has demonstrated improved physical match play performance following an improved sprint time performance (40-m sprint) (215) or improved VO_{2max} (216), but to the author's knowledge, no study has investigated the effect of improved strength on physical match play performance.

Several mechanisms could potentially influence why we did not observe an improvement in sprint and jump ability in *paper II*, together with improved peak match speed in *supplementary analysis I*, despite an increase in maximal strength. For the effect on sprint and jump ability, factors such as duration of the intervention (90, 217), combination with other training (218), and influence of concurrent interference (219) are discussed in *paper II*. However, there could potentially be additional factors. The delay between increased physical capacity, and the ability to utilize this capacity in sporting settings is termed "lag time" (220, 221). This lag time is speculated to possibly extend for months, and hence beyond the typical period of experimental studies (220). There is scarce data on female football players in this regard, however, Nimphius, McGuigan and Newton (222) showed that CMJ did not differ following either 96 hours or 14 days of training cessation after a strength training intervention in soft-ball players, questioning whether lag time influences the transfer of strength to new tasks to a large extent. Further, reducing training volume to 50-70% for one to two weeks may potentially increase muscular power (223), rate of force development (224), and thus potentially sprint and jump performance. However, we did not manipulate the overall training volume in *paper I*. To further study whether these potential factors may influence the findings in *paper II*, future investigations should experimentally manipulate the length of MST interventions as well as the length of the lag-time period following MST.

5.2.3 Comparison across sexes

A sport scientist must be aware and reflect upon potential sociocultural biases (225). As indicated by Nimphius (226), sports science must carefully consider potential confounding factors before concluding with phrases where phenomenon's related to training or physiology are regarded as innate to the females. Training background and fitness levels must primarily be presented and evaluated before concluding that "this finding was due to the participants being females". This is important because fitness level is easily modified by training, while sex change requires comprehensive measures not explained in further details here. Another issue may be that strength and conditioning coaches of female athletes are found to be less experienced and less certified compared to that of males (227). Quality and experience of training, and expertise of coaches can definitively affect an individual's physiological traits and motoric skills. To assess some of these issues, a male group of football players are included in *paper III*. Thus, *supplementary analysis II* was added to underscore that these players did not deviate for the female players in *paper II* at baseline for relative strength levels. An important consideration made for doing this was to compare *paper II* and *paper III* in the light of reproducibility.

Reproducibility refer to the ability to obtain the same results as an original study while matching the procedures as closely as possible (228). This is sometimes called "replication". In this thesis, this is emphasized by the inclusion of *paper III*. *Paper III* provides the similar conclusions as earlier papers on the effect of MST, and the following strength level improvement and secondary outcome effects (*i.e*., sprint and jump ability) (61, 99). These findings were reproduced with different staff, on different occasions, with different subjects, using different equipment.

Moreover, the methods in the barbell free-weight group in *paper III* and the MST-group in *paper II* are very similar. Both studies applied the same laboratory, the same equipment for all the test results reported, and were done at the same time of the year. Thus, we can be more confident that the conflicting findings between *paper II* and *paper III* and other studies in males (61, 99) are not due to the equipment in our laboratory. However, the players in *paper III* improved their strength more than the players in *paper II*, which suggests that their larger increase in strength also could explain the conflicting findings. It is recognized that female football research is in an evolving phase, compared to research on male football which is well established (54). Importantly, it is not known whether applying research knowledge from male football to female football will provide a favourable understanding of the sport and the underlying training for performance (170). For example, when comparing teams of different sexes playing at the same level, lower training volumes are reported for females compared with males (54). Nevertheless, fitness level in form of relative maximal strength did not explain the different outcomes in the *paper II* and *paper III,* since relative maximal strength were not statistically different at baseline.

If we compare the data published and summarized to date on the effect of strength training in female and male football players (61, 90), the findings in *paper II* and *paper III* in this thesis align with those conclusions. That is, strength training improves jump and sprint ability in male football players (61), whereas this is unclear for female football players (90). Thus, one may speculate whether female football players should directly adopt training methods from research on male football players. Nevertheless, recent papers have explicitly stated that their findings from strength training research in male football players should not be generalised to female football players (229), which is an important step towards research-based practice for female football players. As discussed in *paper II*, most of the studies to date that have shown an improvement in strength and jump ability in female football players have included plyometric training. That was further confirmed in a recent meta-analysis, where Pardos-Mainer *et al.* (90) concluded that plyometric training provided better benefits than strength training to improve sprint and jump ability in female football players. This may be why we observed no change in sprint time and CMJ height in *paper II.*

5.2.4 Detraining and COVID-19

Although an increase was apparent in the volume of strength training carried out during the COVID-19 lockdown in *paper IV*, this training was not MST. The maintenance of strength and strength derivatives, suggests that MST is not a prerequisite to maintain strength, sprint speed and jump height performance for female football players. One could expect this to be due to the low initial strength level in these players, but the maximal strength in *paper IV* (104 kg) was not largely different from what is previously reported for the most successful female team in Norway (112.5 kg) applying the same methods (89). However, initial strength level will probably affect the degree of detraining observed when MST ceases (121). In this regard, the strength level for the players in *paper IV*, was lower than the strength level observed in *paper II* after MST (137 kg). Hence, although speculative, maximal strength may have been more susceptible for detraining if the players in *paper IV* had a higher initial strength when the lockdown occurred. Following this assumption, when male players reduced the frequency of MST, maximal strength decreased over a period of 12-weeks (121), which is the same duration as our pre-to post-test duration in *paper IV*. Interestingly, in contrast to *paper IV*, this decrease in males following MST cessation, was followed by a reduction in sprint time performance (121).

Scarce data is yet published of the effects of the COVID-19 related lockdown period on strength and physical match play performance in football players. Although detraining of physical qualities was expected during the conditions imposed by the pandemic (125, 126, 230), few and conflicting findings reporting actual data on this assumption are recently published. In *paper IV*, we observed no change in maximal strength, and to the author's knowledge, this is the only report on change in maximal dynamic strength for football players during the COVID-19 lockdown. However, eccentric strength was reported to decline during the lockdown in male football players (231), indicating some loss of force generating capacities, as suggested by Mohr *et al.* (125), and in contrast to findings in *paper IV.*

For changes in jump height during the COVID-19 pandemic lockdown period, our findings in *paper IV* of no change (28.2 cm vs 26.8 cm) over 12 weeks corroborate the findings in male players, where CMJ height (39.9 cm vs 39.7 cm) did not change during 15 weeks of isolated training during the pandemic lockdown (230). However, another study in male players confirmed this findings, but, when the changes in the underlying force measures were compared against changes of competitive periods before and after the lockdown, absolute maximum power changes declined (232). In *paper IV,* we observed no changes in maximum power over the course of the lockdown, in line with findings of Rampinini *et al.* (232). However, we did not compare the changes during the lockdown period with changes during the surrounding competitive periods, as Rampinini *et al.* (232). Therefore Rampinini *et al.* (232) concluded that home-based training during lockdown was insufficient to maintain power, while we in *paper IV* concluded the opposite. In both *paper IV,* and in the study by Rampinini *et al.* (232), weekly total training volume was~20% lower during the lockdown compared to a normal training/competitive period, and both studies applied bodyweight based strength training during the lockdown. A notable difference between the studies were that the weekly absolute training volume in the study of Rampinini *et al.* (232) was higher both in a training/ competitive period (~480 min), and during the lockdown (~380 min), compared with *paper IV* (~291 min during normal training, and 233 min during lockdown). Moreover, in their paper, a normal training period consisted of 1-2 weekly strength training sessions of systematic use of flywheel devices, which they not had access to during the lockdown. Flywheel devices has been demonstrated to positively influence power in a systematic review (233). No such systematic use of flywheel devices during the training period to the lockdown was reported for the female team in *paper IV*, which may explain the diverse findings.

5.2.5 Considerations and limitations

It could be speculated that although maximal dynamic strength and MST with half-squats (>85% of 1RM) are shown to be related to (65), and, associated with an improvement in linear sprint (99), they may poorly reflect change of direction (COD) abilities (234). Football matches consists of over 700 changes of directions (235), which makes it tempting to speculate whether other strength training methods could provide more effective methods to improve this quality, and thus be related to accelerations and decelerations, together with other measures of the quality of these changes of direction during match play. It is currently unknown what physical determinants best represent COD (234). In *paper III*, we showed that an eccentric overloading exercise was comparable with traditional MST for the improvement in sprint time and jump height for male football players. It is clear that high eccentric strength is prerequisite to decelerate the body from high movement speed to allow fast change of direction (236). Further, the correlation between COD ability tests and strength was higher for eccentric strength than for dynamic strength in female basketball players (237). Future research should investigate (1) the relationship between eccentric strength and physical match play performance in female football players, and (2) the effect of eccentric overload on sprint time, jump height and COD ability, as well as physical match play performance in female football players.

Football is considered one of the most complex sports in the world (238), requiring an integration of different tactical, technical and physical abilities (14). Tactical and technical effectiveness have been suggested to play a greater impact on football performance and match results than physical match play performance (239).

In *paper I* and *supplementary analysis I*, we use tracking data providing variables such as high intensity running distance to measure the hypothetical construct "physical match play performance" which is based on both logical valid rationales as well as constructs with competitive level, as described in the introduction. Mackenzie and Cushion (173) have critically reviewed physical match play performance data management and challenges with reductionistic approaches inherent to positivism, where isolated performance related variables are studied in complex sports such as football. For example, in order to demonstrate a causal relationship between physical match play performance and football performance, an increase in the ability to perform physical match play performance variables must precede an increase in football performance (more matches won, higher league ranking etc.) (15). Most of our understanding of the unpredictable and variable nature of football, is based on research derived from males. For example, factors such as ball possession, the scoreline, team success, and early dismissal (240) as well as environmental factors may influence physical match play performance, as observed for male players (241).

However, a growing body of evidence is emerging for female football, showing a similar picture. For example, high intensity running distance (defined as >16.5 $km \cdot h^{-1}$) has been shown to give a match-to-match variation of 33% (36), indicating a large effect needed to provide practical and meaningful findings in physical match play performance. A myriad of factors could potentially influence this variability in physical match play performance (239). For example, it has been shown that physical match play performance parameters increase if a team wins against a better ranked team, or draws against a lower ranked team (50). As such, contextual factors of football match play may often prevent players from utilizing their full physical capacity (16).

This large disparity between games specifically applies to *supplementary analysis I*, which has a low sample size and demonstrates the limitation of this analysis. The power analysis for that study was calculated on the sample required for sprint change in *paper II*. Criticism of low sample sizes used for physical match play performance exist (173, 242, 243). For example, Gregson *et al.* (242) estimated that in order to find a difference of 10% following an intervention, a sample size of 80 players would be required. Further, as playing position (39) influences physical match play performance in female football (39, 40, 42, 244), consideration should be made when researching and interpreting results, and especially if planning to perform stratified analyses on *e.g.* positions. In order to account for positional differences, analysis was provided for central and lateral players in *paper I* according with previous research (245). An alternative option would be to divide the players into the traditional 5 positional groups: center backs, full backs, center midfielders, wide midfielders and attackers (246). However, this would result in a low number of players in some positions (see descriptive characteristics in table 1, *paper I*), and would therefore require that some positions be excluded from statistical analysis, as shown previously (40). Nevertheless, physical match play performance is only a part of the complex football performance and is influenced by multiple factors beyond just fitness.

Further, it is also important to acknowledge that skillful activities are shown to influence female football performance. One vs one play in defense and offense as well as passing accuracy are shown to affect the match result in females (247). Studies have only recently started to examine the relationship between physiological variables and football related skills. For example, Wing *et al.* (174) found a relationship between squat 1RM and tackle success for male football players. Successful duels have been proposed to be important for match outcome in female football; a relationship not previously observed in male football (19). Therefore, maximal strength may be important for factors other than physical match play performance, and future studies should examine the role of maximal strength for skill execution in female football players, as some of the identified associations (*e.g.*, tackle success) in male football may be even more relevant for female football match outcome.

In an open loop sport such as football, where multiple attributes must be stimulated, Steele, Fisher and Crawford (248) have proposed whether increasing strength is worth the time, energy, and recovery required to make athletes stronger. It has been suggested that in a practical setting, not every football team is able to include strength training in their annual training plan (249). Still, it is the author´s view that when evaluating components for the whole training puzzle, it is important to acknowledge that each MST session could be time efficient, still effective and provide low extra training volume, using as little as 20 minutes to perform 4x4 repetitions in squats, including recovery time (250), and require relatively simple and inexpensive equipment that would be available for most teams (70).

Strength training is included in the current practice of female football teams (18, 67). Consequently, strength is reported to be the most frequently programmed physical component in training programs intended to reduce non-contact injuries in female football players (251). Further, a meta-analysis showed that strength training interventions could decrease sports injuries to one-third compared to without and reduce overuse injuries by half (252). This may enhance overall team performance, as we know from male football that injuries affects a team's success in the league and cups (253). Further, from an injury preventive perspective, it has been suggested that there is still scope to conduct training interventions with heavy loads (*i.e.*, MST) on team-sport athletes (254) in light of recent evidence demonstrating squat relative strength as an identifier for lower extremity injury in collegiate athletes (255). Moreover, strength may influence training tolerance. Physical match play performance is shown to be related to the increase in post-match creatine kinase expression (256, 257). Nevertheless, Owen, Dunlop, Rouissi *et al.* (258) demonstrated that leg strength was associated with lower levels of post- match creatine kinase levels. However, as these findings comes from male football players, this is yet to be elucidated in females.

Although few studies have been conducted to date, explosive actions and strength characteristics seem to be unaffected by the menstrual phase (203, 259), which suggest that timing of testing can be planned without considering this. The research on the influence of menstrual phase for training and adaptations has emerged lately in football. After the FIFA Women´s World Cup in 2019, a large interest has emerged related to this topic (260), and multiple clubs have are already tailoring their training to the menstrual phase of the players (261). However, whether training periodized within the menstrual cycle promotes superior training adaptations compared to non-periodized training is not known, although some studies have found greater increase in strength by emphasizing more strength training in the follicular phase compared with the luteal phase (262-264).

Moreover, the influence of oral contraceptives (OC) on training adaptations is also debated. In general, for the strength training, speed and jump performance, the overall picture is not clear. Romance, Vargas, Espinar *et al.* (265) found adaptations for squat 1RM and CMJ height to not be influenced by whether a trained group consumed OC during strength training or not. The same conclusion is drawn for leg strength adaptations in untrained women participating in strength training (266). Additionally, the role of OC on muscle mass adaptations, being an important contributor in muscle strength, seems unclear. While Riechman and Lee (267) reported that healthy young women who used OC had impaired lean mass gains following strength training, Romance *et al.* (265) only observed an increased muscle mass in the OC. Recent research has also suggested that OC may negatively influence body composition, training adaptations, and recovery in football players (268). Thus, menstrual cycle phase, and OC use may influence performance and adaptations to training. However, to date, there are few studies elucidating this in football players, making it premature to provide practical guidelines for menstrual cycle and training for football performance (35).

Paper I reported additional analysis on central and lateral players, as the physical requirement in these positions probably differs in female football players (39), as also observed in males (245, 269). Information from these sub-analyses may inform which explosive factors that are most relevant for either central or lateral players. Further, such findings may inform coaches and athletes what tests and abilities that are most relevant for the different positions, as well as targeted physical training objectives (270). These analyses should be reproduced with larger sample sizes given our small sample in *paper I.*

The single-group pre-test and post-test design applied in *paper IV* may be considered a weak study design (139). Nevertheless, we can observe whether a change in a performance measure has occurred or not, being the main purpose of the paper. However, the design does not allow us to draw conclusions about causality. The post-measure in *paper IV* was executed prior to the summer holiday to minimize the effect of off-season detraining *per se* (271). Further, creating a control group, preferably randomized, at the same time would have been impossible, as COVID-19 was a global pandemic without any sound warnings of lockdown from governmental authorities.

6 Conclusion

The aims of the thesis were to study association between strength (1 repetition maximum (1RM) half-squat strength), 5-, 10- and 15 m sprint, countermovement jump (CMJ)), and physical match play performance in high level female football players. Further, the next aim was to investigate whether maximal strength training result in improvements in strength, and whether it associated with improvements in sprint and jump height performance, as well as physical match play performance in female football players. Next, we investigated whether previous findings reported following MST for male players reproduced in our lab in *paper III*, as well as how those these findings compare with findings in female players from *paper II*. Finally, an aim was to study the effect of a prescribed unsupervised 12-week home- and group-based training program without gym facilities, for 1RM half-squat strength, CMJ, and 5 m, 10 m, and 15 m sprint time in female high-level football players during a period without full contact football training. Our findings indicate maximal strength is of minor importance for physical match play performance, and far lower than other test variables, such as CMJ and sprint times, which were associated with physical match play performance. MST is feasible and effective for increasing maximal strength in female football players, however the importance of MST for sprint and jump performance in female football players was minimal. We found a limited impact of exercise including MST, on sprint times ≤ 15 m, and jump height. When male players of the same relative strength level at baseline carried out MST, an improvement in sprint and jump performance was found. Further, excluding systematical MST and restricting access to training gyms over a period of COVID-19 lockdown, with the prescription of only body weight exercises and without maximal strength training, did not negatively influence maximal strength, sprint times or jump height in female high-level football players. This has implications for periods without access to football- or strength training facilities.

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Paper I

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SPECIAL ISSUE ARTICLE

WILEY

Associations between maximal strength, sprint, and jump height and match physical performance in high-level female football players

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Studies on females' decisive physical components to physical match-play performance are sparse and only emphasize endurance tests. Thus, the influence of maximal strength and power on physical performance during match-play is currently unknown. The aim of this study was to assess the association between one repetition maximum (1RM) half squat strength, 5-, 10-, and 15-m sprint times, countermovement jump (CMJ) height, and physical high-intensity match-play performance in high-level female football players. Thirty-seven female high-level football players completed 1–2 football matches with physical performance measured by local positioning tracking. Correlations were assessed between physical match-play performance variables (total distance covered, running distance, high-intensity running distance, sprinting distance as well as acceleration and deceleration counts, and peak speed) and laboratory tests (half squat 1RM, 15-m sprint, and CMJ). We found no correlation between 1RM and physical match-play performance. Further, 10-m- and 15-m sprint time ($r = -0.56$, $r = -0.56$, $p < 0.001$) and CMJ jump height ($r = 0.50$, $p < 0.01$) strongly correlated with peak match speed. Further, there was a moderate correlation between 15-m sprint time and ACC ($r = -0.43$, $p < 0.05$). 5-m sprint time did not correlate with physical match-play performance. Laboratory-based sprint and jump performance, but not maximal half squat strength, showed moderate to large correlations with high-intensity physical match-play performance measures in high-level female football players.

KEYWORDS

exercise physiology, external load, local positioning system, neuromuscular performance, one repetition maximum, power, resistance training, Soccer

1 | INTRODUCTION

Important physical capacities in football include aerobic and anaerobic endurance, strength and power, and their derivatives acceleration, sprinting, and jumping.[1] The association between tests of these capacities and physical match-play performance could provide important information for players and coaches and may be a standardized and relevant practice for tracking development of physical capacities in football players. For male players, endurance field tests,[2,3] jump tests,[4,5] and sprint performance tests[6] are all associated with physical match-play performance assessments, whereas strength associations are only studied during small-sided games [7] and for the ability to resist fatigue during match-play.[8]

Females have different body composition than males, where especially males have more muscle mass than females.[9] Additionally, these body compositional differences also comprise different distribution of muscle fiber types, where males inherent greater proportion of the higher threshold, fast twitch fibers,[10] and a lower proportion of slow twitch fibers[11] than females. Consequently, in general, males are stronger,[10] sprint faster, and jump higher[12-14] than females. This also results in different physical match-play performance outputs likely due to lower peak running speed and lower anaerobic power and capacity in females. Hence, it may also result in different associations between laboratory and field-based tests and physical match-play performance assessments. For example, while maximal oxygen uptake is found to be of lower importance for physical match-play performance in male football players, it is correlated with high-intensity running in female football.[15]

In a recent systematic review evaluating the association between laboratory and field-based tests and match-play physical performance, 27 (two studies) out of the 991 players included were females,[16] which highlights the importance of evaluating field-based tests and match-play performance in female football players. Moreover, these two studies assessed associations between endurance-related tests and match-play physical performance.[15,17] Thus, associations between strength and strength derivatives tests, and match-play physical performance can only be generalized from male to female football players. Consequently, studies on strength and strength derivatives for female football players are warranted.[18,19] Considering the inherent differences in body compositional nature between females and males, sex differences between power performance and physical match-play may also be evident, such as observed for maximal oxygen uptake.[15] Consequently, the aim of this study was to assess associations between (1) maximal strength (one repetition maximum (1RM) half squat strength), (2) 5-, 10-, and 15-m sprint, and (3) countermovement jump (CMJ), and physical high-intensity match-play performance assessed as total distance covered, running distance, high-intensity running distance, sprinting distance as well as acceleration and deceleration counts, and peak speed in high-level female football players.

2 | MATERIALS AND METHODS

2.1 | Design and procedure

In this cross-sectional study, the associations between laboratory tests of maximal strength, jump height, and sprint times, and physical performance during friendly 11 vs 11 football match-play were examined. The laboratory tests were carried out over two separate days where 15-m sprint time with 5-m and 10-m split times and CMJ height were tested at day 1, and maximal half squat strength 1RM was tested at day 2. Test days were separated by at least three days. Following all laboratory tests, matches were played with at least 48 h of recovery and within maximum four weeks. Participant inclusion criteria for our analyses were (1) 90 min of playing time in at least one match and (2) complete at least one of the laboratory tests between >48 h to four weeks before the matches.

2.2 | Subjects

Thirty-seven outfield players were included, where 25 players completed one, and 12 players completed two 90-min friendly matches in one given position. One player lost the first 5 min of the match due to error with the tracking device, and for this participant, only peak speed was carried forward for analysis. Additionally, 34 players completed all three laboratory tests, while three participants only completed the CMJ and sprint test. The teams were playing at level two and three in Norway. We contacted the teams' coaches and invited their teams to participate. When informing the players about the study's purpose and the associated risks and benefits, all eligible players who were invited accepted the request to participate. Exclusion criteria were players with injuries making them unable to perform the matches and/or tests, as well as players performing <90 min of playing time. The players' characteristics are described in Table 1. The study complied with the Declaration of Helsinki. All participants gave written informed consent.

2.3 | Sprint test

Prior to each test day, the players refrained from high-intensity exercise for 48 h. On their first visit to the laboratory, the players arrived in the afternoon, where body mass (Seca 813, Seca GmbH & Co.) and height (Seca 217, Seca GmbH & Co.) were measured before they performed a warmup consisting of 14 min of self-selected, self-perceived low-intensity cycling (7 min) and running (7 min). Thereafter, three sprint acceleration attempts of 15 m at approximately 95% of maximal effort were carried out on artificial grass, with an easy walk back to start. Single-beam photocells (ATU-X, IC control AB) mounted to the wall at every 5-m split recorded the sprint times. The first photocell was placed 20 cm above the ground with the following 5-m, 10-m, and finishing 15-m photocells placed 100 cm above the ground. The players

TABLE 1 Descriptive characteristics of the study participants (mean ± SD)

Age (years)	18.4 ± 3.6
Body mass (kg)	61.8 ± 5.4
Height (cm)	167 ± 5
Positions	
Full backs (n)	5
Center backs (n)	7
Center midfielders (n)	12
Wide midfielders (n)	9
Center forwards (n)	4
Variables	
CMJ (n)	37
15-m sprint test (n)	37
1RM (n)	34
TD, RD, HIR, Sprinting, ACC/DEC (n)	36
Peak speed (n)	37

Data are shown as mean ± SD and frequency (n).

Abbreviations: 1RM, 1 repetition maximum; ACC, acceleration counts; CMJ, countermovement jump; DEC, deceleration counts; HIR, high-intensity running distance; TD, total distance.

started 30 cm behind the first photocell, initially triggering the timer when breaking the sensor. The players decided when to start the sprint, and a minimum of three minutes were given between in total three attempts. The fastest 15-m sprint with its split times was carried forward for final analyses.

2.4 | Countermovement jump test

Following >3 min rest from the sprint trials, a CMJ test was performed on a portable force platform (Hur-Labs, ALU4, Finland), connected to a computer, and recorded in the manufacturer´s software (Force platform software suite, HURlabs oy, Kokkola, Finland). All players carried out two jumps with their hand placed on the hips, with a self-selected depth of the countermovement, interspersed by minimum three minutes rest. Each player was verbally encouraged to perform the jump with maximal effort. The highest jump was recorded as their CMJ height.

2.5 | Maximal half squat strength

On their second visit to the laboratory, following the same warmup as prior to the sprint test (14 min self-selected low intensity), maximal strength was assessed by 1RM in half squat. An Olympic Bar (20 kg, T-100G; Eleiko, Halmstad, Sweden) and a squat rack were used for 1RM testing. Prior to starting their 1RM trials, the players warmed up with 10 repetitions at ~ 50% 1RM. A sports scientist (SP) used a hand-held goniometer to ensure a ~ 90° knee angle between femur and tibia on every 1RM trial. An image of the ~ 90° knee angle squat exercise is illustrated in Supplementary Materials. The trials started in standing position with a weight decided by the researcher. For every approved set, the weight was increased with 5–10 kgs. Recovery between every set was set to >3 min, and the highest accepted lift was recorded as 1RM.

2.6 | Physical performance during match-play

Prior to each match, the players refrained from high-intensity exercise for 48 h. All matches were played on artificial grass at the same football stadium (105 × 68 m) during pre-season at 69 degrees north in temperatures varying from −12 to 5 degrees Celsius. All matches started between 19:00 and 21:00. The two halves were 45 min with no added time. The coaches decided on the tactical systems, and positions for the players. Each match was monitored using a stationary radio-based tracking system capturing positional data at 20 Hz (ZXY Sport Tracking System, Trondheim, Norway) as described earlier.[20,21] The system is found reliable and has a good coefficient of variation (CV) being 1% for total distance and 3.1% for high-intensity running distance.[20] Our selected physical match-play performance variables total distance (TD), running distance (RD), high-intensity running distance (HIR), sprinting distance (SD), acceleration counts (ACC) deceleration counts (DEC), and peak speed were chosen for further analysis. The following locomotion speed and acceleration cutoffs were applied: RD (>12km h^{-1}), HIR (>16 km h^{-1}), sprinting (>20 km h^{-1}),[22] accelerations/ decelerations (ACC/DEC; a positive or negative change of speed more than 2 m s^{-2}, lasting more than 0.5 seconds).[23] For players performing two matches, the data were averaged except for peak for peak match speed, where the highest speed was included for the final analyses. For positional characteristics, players were divided into central (center backs, center midfield, forwards) and lateral (full backs, wide midfielders) positions for correlational analysis.

2.7 | Statistical analyses

Normality distribution was examined with visual inspection of Q-Q plots together with the Shapiro-Wilk normality test (all $p > 0.05$ except for high-intensity running distance ($p = 0.007$) and sprint distance (p=0.034). Pearson's correlation coefficients (r) were used to assess the association between physical match-play performance (total distance,

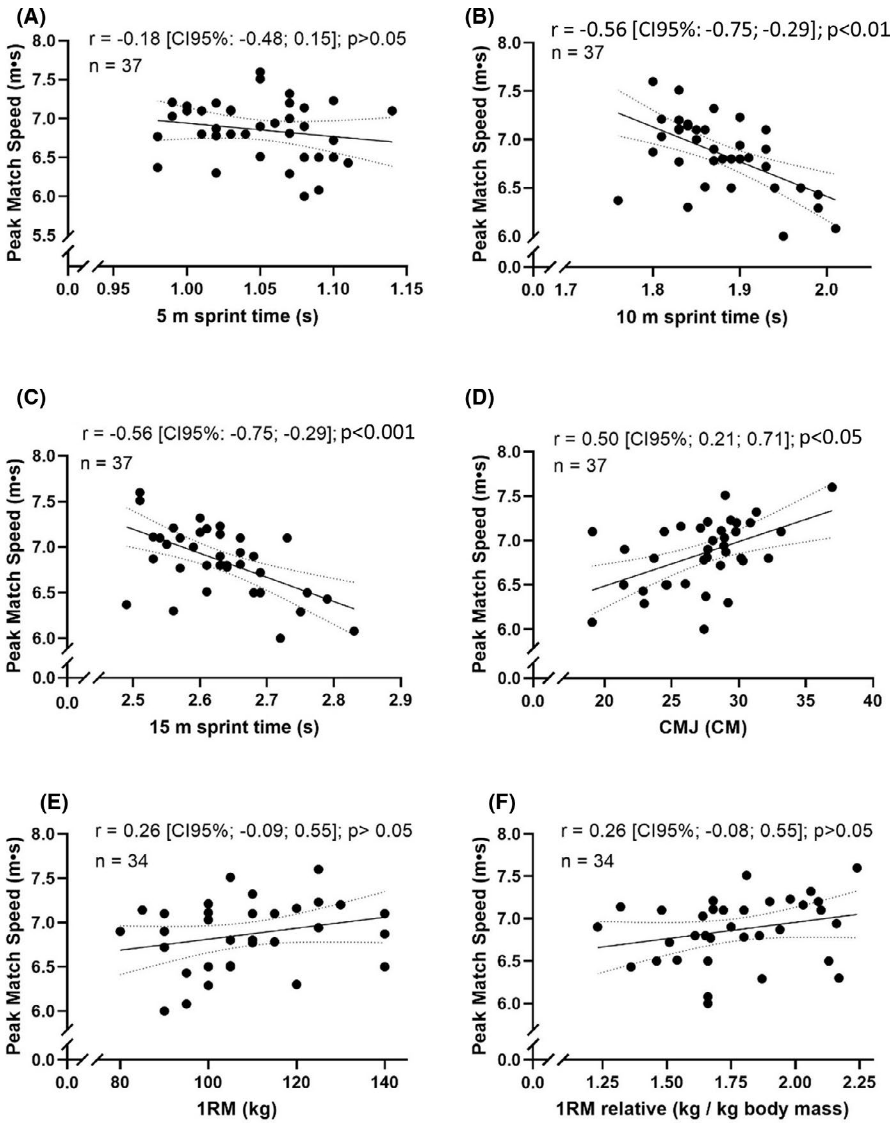

FIGURE 1 Scatterplots with regression lines with 95% CI, and correlation coefficients between peak match speed and 5-m sprint time (A), 10-m sprint time (B), 15-m sprint time (C), CMJ (D), 1RM half squat strength (E), and scaled 1RM / body mass (F), for players of both lateral and central positions pooled. CI, confidence interval; CMJ, countermovement jump; 1RM, one repetition maximum

high-intensity running distance, sprint distance, acceleration counts, decelerations counts, and peak match speed) and laboratory-based assessments (1RM, CMJ, and 5-, 10-, and 15-m sprint times), as well as between the laboratory tests (15-m sprint test, CMJ, and 1RM). In the non-normally distributed variables (high-intensity running distance and sprint distance), Spearman´s rho (ρ) correlation was used. A correlation (r/ρ) of ≥ 0.1 was considered small, ≥ 0.3 moderate, and ≥ 0.5 large.[24] To test for significance of the difference between two correlation coefficients (ie, central vs. lateral positions on the same variables), the Fisher r-to-z transformation was used. This was also used for Spearman´s rho in accordance with others.[25] To decrease the false discovery rate, the p-values were adjusted using the Benjamini-Hochberg method for each laboratory variable (7 pairwise comparisons in each test) for both pooled group correlations, correlations within positions, and for z comparisons between positions.[26] All data are presented as mean ± standard deviations (SD) or r and ρ unless otherwise is stated. The Statistical Package for Social Sciences (version 26.00; IBM Corporation) and the functions r.test and p.adjust (packages psych and stats in R) (R core team, 2021)[27] were used for all statistical analyses.

3 | RESULTS

For the pooled sample, we found no correlation between 1RM and physical match-play performance. Further, 10-m- and 15-m sprint time (r = −0.56, r = −0.56, $p < 0.001$), and CMJ jump height (r = 0.50, $p < 0.01$) strongly correlated with peak match speed (Figure 1). Further, there was a moderate correlation between 15-m sprint time and ACC (r = −0.43, $p < 0.05$). 5-m sprint time did not correlate with physical match-play performance. Stratified analyses of lateral and central positions are presented in Table 2 (descriptive characteristics) and Table 3 (correlation analyses). There were no differences in correlations between positions for any of the variables (all $p > 0.05$).

There were moderate to large correlations between CMJ and the split times during the 15-m sprint test: 5 m

TABLE 2 Match and laboratory variables for lateral, central, and all players

Variable	Lateral players ($N = 14$)	Central players ($N = 23$)	All ($N = 37$)
TD (m)	9927 ± 1026	10051 ± 848#	10003 ± 909
Running (m)	1726 ± 433	1790 ± 414#	1765 ± 417
HIR (m)	1099 ± 375	792 ± 266#	912 ± 343
Sprinting (m)	272 ± 112	171 ± 125#	211 ± 129
ACC (counts)	31 ± 14	22 ± 9#	26 ± 12
DEC (counts)	41 ± 17	29 ± 10#	34 ± 14
Peak match speed (m·s)	6.94 ± 0.25	6.80 ± 0.43	6.86 ± 0.38
15-m sprint			
5-m sprint time (s)	1.05 ± 0.03	1.05 ± 0.04	1.05 ± 0.04
10-m sprint time (s)	1.89 ± 0.05	1.87 ± 0.07	1.88 ± 0.06
15-m sprint time (s)	2.63 ± 0.06	2.63 ± 0.09	2.63 ± 0.08
CMJ jump height (cm)	27.32 ± 3.72	27.42 ± 3.90	27.38 ± 3.78
1RM 90° squat (kg)	107 ± 16*	110 ± 16†	109.1 ± 16.1
1RM 90° squat (kg/mb$^{-0.67}$)	6.80 ± 1.03*	6.95 ± 0.95†	6.89 ± 0.97
1RM 90° squat (kg/mb kg^{-1})	1.75 ± 0.28*	1.78 ± 0.25†	1.77 ± 0.26

Data are shown as mean ± SD.

Abbreviations: 1RM, 1 repetition maximum; ACC, acceleration counts; CMJ, countermovement jump; DEC, deceleration counts; HIR, high-intensity running distance; TD, total distance.

* = n 13;

= 22;

† = n 21.

(r = −0.48, p = 0.002), 10 m (r = −0.66, p =< 0.001), and 15 m (r = −0.72, p =< 0.001) (r = −0.72 (p =< 0.001). There were no significant correlations between the split sprint times and 1RM (all $p > 0.05$). There were moderate correlations between CMJ height and scaled 1RM squat (kg/mb$^{-0.67}$) (r = 0.41, p = 0.015) and 1RM (kg/mb kg^{-1}) (r = 0.43, p = 0.011).

4 | DISCUSSION

This cross-sectional study is to our knowledge the first study to assess laboratory-based lower limb strength and strength derivatives, with physical match-play performance in high-level female football players. We found large correlations between peak match speed, and 10-m and 15-m sprint time, as well as CMJ height. A moderate correlation was found between 15-m sprint time and ACC. These findings are applicable to physical coaches of female football teams, which should focus on relevant assessment tools to monitor the players' physical condition and development.

5 | STRENGTH

There were no associations between maximal half squat strength and physical match-play performance. Thus, it seems that dynamic lower limb muscle strength does not play a central role in physical match-play performance.

A previous study in male football players reported a moderate correlation between isometric maximal strength and small-sided games performance.[7] They assessed physical performance in the playing formats 8 v 8 and 4 v 4, while we assessed it during 11 v 11 matches. The above-mentioned previous study found a moderate correlation between strength and acc.[7] When the number of players involved, and field size during game play decrease, there is an increase in the number of accelerations/decelerations.[28] Decelerations are shown to be muscularly taxing,[29] and therefore, a high strength level could potentially be related to the ability to perform decelerations. However, their findings are in contrast to ours as we did not observe a positive correlation between accelerations/decelerations and maximal strength. Another study reported isokinetic strength to be correlated with match-play physical performance in the context of fatigue parameters, where greater levels of strength were related to an ability to maintain performance toward the end of matches.[8] This suggests that strength may be related to the ability to perform accelerations during small-sided games, as well as the ability to resist physical performance fatigue during match-play, at least in males.

Moreover, whether strength assessments are evaluated as dynamic or static, isometric, or isokinetic, may influence the interpretation of the importance of strength for football performance. On the one hand, measures of isometric force

TABLE 3 Correlations between physical match-play performance and laboratory tests for lateral and central positions

	5-m sprint time (s)	10-m sprint time (s)	15-m sprint time (s)	CMJ (cm)	1RM (kg)	1RM (kg/ mb$^{-0.67}$)	1RM (kg/mb kg^{-1})
Lateral positions							
TD (m)	*r* −0.23 (0.47)	*r* −0.39 (0.17)	*r* −0.20 (0.54)	*r* −0.09 (0.94)	*r* −0.42 (0.49)	*r* −0.21 (0.99)	*r* −0.10 (0.93)
Running (m)	*r* −0.33 (0.47)	*r* −0.41 (0.17)	*r* −0.18 (0.54)	*r* −0.04 (0.94)	*r* −0.34 (0.49)	*r* −0.12 (0.99)	*r* −0.02 (0.96)
HIR (m)	ρ −0.40 (0.16)	ρ −0.58 (0.03)	ρ −0.47 (0.09)	ρ 0.28 (0.34)	ρ −0.37 (0.21)	ρ −0.08 (0.79)	ρ 0.08 (0.79)
Sprinting (m)	ρ −0.21 (0.47)	ρ −0.54 (0.12)	ρ −0.45 (0.15)	ρ 0.32 (0.61)	ρ −0.32 (0.49)	ρ −0.10 (0.99)	−0.12 (0.93)
ACC (counts)	*r* −0.27 (0.47)	*r* −0.47 (0.17)	*r* −0.55 (0.07)	*r* 0.02 (0.94)	*r* −0.33 (0.49)	*r* −0.28 (0.99)	*r* −0.25 (0.93)
DEC (counts)	*r* −0.21 (0.47)	*r* −0.42 (0.17)	*r* −0.55 (0.07)	*r* 0.20 (0.86)	*r* −0.04 (0.89)	*r* 0.04 (0.99)	*r* 0.08 (0.93)
Peak match speed (m·s)	*r* −0.33 (0.47)	*r* −0.76 (0.007)	*r* −0.70 (0.04)	*r* 0.55 (0.28)	*r* −0.22 (0.67)	*r* 0.01 (0.99)	*r* 0.11 (0.93)
Central positions							
TD (m)	*r* 0.45 (0.84)	*r* −0.02 (0.93)	*r* 0.01 (0.96)	*r* −0.23 (0.67)	*r* −0.11 (0.81)	*r* 0.04 (0.86)	*r* 0.12 (0.62)
Running (m)	*r* −0.13 (0.77)	*r* −0.14 (0.63)	*r* −0.12 (0.70)	*r* −0.02 (0.94)	*r* −0.01 (0.99)	*r* 0.16 (0.60)	*r* 0.23 (0.46)
HIR (m)	ρ −0.04 (0.85)	ρ −0.28 (0.21)	ρ −0.25 (0.26)	ρ −0.03 (0.91)	ρ 0.41 (0.08)	ρ 0.45 (0.04)	ρ 0.41 (0.08)
Sprinting (m)	ρ −0.14 (0.77)	ρ −0.37 (0.19)	ρ −0.29 (0.33)	ρ 0.17 (0.67)	ρ 0.47 (0.14)	ρ 0.45 (0.16)	ρ 0.32 (0.37)
ACC (counts)	*r* −0.33 (0.77)	*r* −0.49 (0.07)	*r* −0.46 (0.11)	*r* 0.33 (0.46)	*r* 0.35 (0.30)	*r* 0.41 (0.16)	*r* 0.41 (0.37)
DEC (counts)	*r* −0.22 (0.77)	*r* −0.35 (0.19)	*r* −0.33 (0.33)	*r* 0.09 (0.79)	*r* 0.09 (0.81)	*r* 0.21 (0.53)	*r* 0.25 (0.46)
Peak match speed (m·s)	*r* −0.16 (0.77)	*r* −0.57 (0.04)	*r* −0.55 (0.04)	*r* 0.52 (0.07)	*r* 0.47 (0.14)	*r* 0.42 (0.16)	*r* 0.36 (0.37)

r = Pearson´s correlation, *ρ* = Spearman´s rho. P-values (in brackets) are adjusted for multiple comparisons.

Abbreviations: ACC, acceleration counts; DEC, deceleration counts; HIR, high-intensity running distance; TD, total distance.

development have been reported [7]; on the other hand, isokinetic strength has been applied by researchers.[8] However, it is argued that the most functional strength measurement for football players is dynamic strength, which replicates the movements in match-play.[19] This is in line with findings of dynamic strength being more related to sport-specific sprinting than isometric strength.[30]

6 | SPRINT

For the first time, we display the relationship between a sprint test and physical performance during match-play for female football players. Thus, short sprint assessment in female football may be a relevant assessment tool for monitoring physical capacity and the effect of physical conditioning. Sprinting performance in football is usually divided into an initial acceleration phase (5–10 m) and a longer maximal speed phase (20–40 m).[31] However, most sprints during football match-play are relatively short (Griffin et al, 2020), and our findings indicate that 10-m sprint may be a suitable test relating to peak match speed performance in female football. However, shorter distances during testing are not necessarily better, as 5-m sprint time not was correlated with match-play peak speed in our study, which is consistent with a study in male players.[5] At the same time, the association between sprint performance and physical match-play seems to be inconclusive in the literature.[32,33] Future studies should assess 20–40-meter sprinting time and physical match-play performance to evaluate the importance of testing longer sprint distance in female football.

7 | COUNTERMOVEMENT JUMP

We did not observe any correlation between CMJ and physical match-play performance, which is in contrast to findings in both youth and senior male players,[4,5] except for a strong correlation between CMJ and peak match speed for the players as a pooled group. As we observed a non-significant large correlation ($r > 0.5$) in strata analysis of positions, which was similar to the effect in the pooled group, this may be due to low statistical power, as finding a large effect ($r > 0.5$) with 80% and an alpha of 0.05 would require a sample of 20 players. Thus, we interpret no lower importance of CMJ and peak speed by position in female football. However, large intra-game variations in high-intensity physical performance between positions have been observed previously [34]; thus, our interpretation should be confirmed by future research. Furthermore, although vertical jump and linear sprinting are considered independent skills by some,[35] they are associated in this study. This finding is inconclusive for male players.[6,36] Further, there are contradictive findings on whether CMJ height separates players of different competitive levels in female football.[37,38] It may be that CMJ is more important for other traits than for physical match-play performance, such as headers, which is indicated for youth male players.[39]

Finally, previous studies assessing associations between laboratory-based tests and physical match-play performance have differed between sexes, as described above for maximal oxygen uptake.[15] This indicate that there may be differences in which and how energy systems and neuromuscular factors relates to physical match-play performance between sexes in football, which warrants further and detailed investigations to provide an equal knowledge base for training and performance development for both sexes.

7.1 | Limitations

The relatively small sample size, and low number of matches in this study can be regarded as a limitation, which may be illustrated by a large non-significant correlation between CMJ and peak speed in strata analyses. A large number of players representing all playing positions is important for correlational analysis, since there have been found large inter-game variations in high-intensity physical match-play performance between positions.[34] Further, as team sports with opponents introduces many degrees of freedom, it is important to consider physical performance at best as a proxy, and not a direct measure of football performance (*ie*, wins/losses), or alternative measures that is linked to performance (points, goals scored, *etc*.).

8 | CONCLUSION

In this cross-sectional study, laboratory-based sprint performance, but not maximal half squat strength, was associated with measures of high-intensity physical performance during matches in high-level female football players. CMJ was associated with peak match running speed. These findings suggest that 15-m sprint and CMJ tests can be used with relevance to physical match-play performance in female football players.

9 | PERSPECTIVE

Although not examined here, the physical tests in this study may be relevant for sports performance in other ways, which together with its relationship with physical performance should be recognized by the practitioners. For example, CMJ height is associated with heading success and 1RM squat with tackling success.[39] 1RM squat strength is also found to predict future injuries.[40] Nevertheless, our findings are applicable to practitioners when selecting tests to monitor physical condition of female football players.[6]

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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Paper II

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Improved maximal strength is not associated with improvements in sprint time or jump height in high-level female football players: a cluster-randomized controlled trial

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RESEARCH ARTICLE Open Access

Improved maximal strength is not associated with improvements in sprint time or jump height in high-level female football players: a cluster-randomized controlled trial

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Abstract

Background: Maximal strength increments are reported to result in improvements in sprint speed and jump height in elite male football players. Although similar effects are expected in females, this is yet to be elucidated. The aim of this study was to examine the effect of maximal strength training on sprint speed and jump height in high-level female football players.

Methods: Two female football teams were team-cluster-randomized to a training group (TG) performing maximal strength training (MST) twice a week for 5 weeks, or control group (CG) doing their regular pre-season preparations. The MST consisted of 3–4 sets of 4–6 repetitions at ≥85% of 1 repetitions maximum (1RM) in a squat exercise. Sprint speed and jump height were assessed in 5-, 10- and 15 m sprints and a counter-movement jump (CMJ) test, respectively. Nineteen participants in TG (18.3 ± 2.7 years) and 14 in CG (18.3 ± 2.4 years) completed pre- and posttests and were carried forward for final analyses.

Results: There was no improvement in neither of the sprint times ($p > 0.36$), nor jump height ($p = 0.87$). The players increased their 1RM in squats (main of effect of time: $p < 0.00$, ${}_p\eta^2 = 0.704$), and an interaction effect of time x group was observed ($p < 0.00$, ${}_p\eta^2 = 0.516$) where the TG increased their 1RM more than the CT (between subjects effects: $p < 0.001$, ${}_p\eta^2 = 0.965$).

Conclusions: MST improved maximal strength in female football players to a large extent; however, the improvement in maximal strength did not result in any transference to sprint speed or jump height.

Trial registration: This study was registered at clinicaltrials.gov PRS (Protocol registration and results System) with the code NCT04048928, 07.08.2019, retrospectively registered.

Keywords: Soccer, Sprint, Counter movement jump, 1RM, Squats

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Background

The intermittent nature of football demands complex physiological taxations [1]. Sprint performance seems to be an important factor, which discriminates between competitive level of players where elite female football players sprint faster compared with lower level players [2, 3]. Over the course of a football match, elite female football players sprint (≥25.1 km·h^{-1}) ~ 200 m, distributed in ~ 30 bouts, of which 95% are sprints under 10 m [4], and interestingly, the speed of the sprints has increased for female football players over the last two decades [5], emphasizing the growing importance of sprints in female football.

Approaches for improvements in sprint are many, including sprint training, explosive movements and strength training (ST) [6–8]. Traditionally, ST regimes for developing speed and explosiveness have mainly consisted of repetitions of high velocities and low loads [9]. However, training regimes consisting of training with high loads and low velocity repetitions, usually between 3 and 5 sets of 4–6 repetitions ≥85% one repetition maximum (1RM) has emerged as a supplement and/or replacement to the low-load high velocity training [10]. The high load low velocity strength training, usually expressed as maximal strength training (MST), is effective for improving maximal strength [11], and may also result in improvements in muscle power and rate of force development in male football players [12]. The rationale behind this training modality for improvements in explosive actions builds on the significant relationship between 1RM and movement velocity, sprint performance and jump height [13, 14]. In contrast to the principle of training specificity, training of maximal strength in a nonspecific movement tempo combined with the specific movement itself, is more effective than just training the fast movement alone [15]. The effect from MST on power actions could be explained by an improved neural drive to the muscles involved [16, 17] due to the training being performed with maximal intended velocity combined with a load approaching the upper limits of motor unit recruitment [18].

Moreover, the goal of ST is often increased muscle mass [19], however, when comparing conventional hypertrophy training (60–70% of 1RM, 8–12 repetitions) with MST, MST is superior concerning gains in both 1RM and rate of force development [11, 20]. Additionally, an increased muscle mass may be detrimental for sports performance involving endurance, such as football, due to the increased body mass. Thus, improving strength with minimal hypertrophy should be favourable, as this will lead to an increased relative strength. According to Newton's second law of motion, an increased relative strength should improve jump height and sprint speed. Minimal hypertrophy in relation to maximal strength gains is best achieved by ST with high loads and low volume [11, 20–22].

In male football players, studies have reported a favorable effect on both 1RM, sprint and jumping performance following MST [20, 23]. Although females and males possess diverse levels of anabolic hormones, they do in general respond similarly after training interventions in most strength outcomes [24]. However, there are reports of a larger relative increase in females compared to males when the same ST is applied [25]. Further, on the muscle fiber level, heavy resistance training is reported to induce hypertrophy for type IIX fiber cross-sectional area in young males only, when compared with young females [26], indicating potential gender differences in response to ST. The effect on strength, sprint and jump height performance following MST in female football players is still to be elucidated. Thus, the aim of this study was to examine if improvement in maximal strength is associated with improvements in sprint and jump height performance following MST.

Methods

In this cluster-randomized controlled trial, two football teams (playing at level 2 and 3 in Norway) was invited to participate. The study were conducted during the last part of the pre-season preparations, ending 1 week before first seasonal competition. The training group (TG) performed MST training carried out as free-barbell squats twice a week over 5 weeks in addition to the planned pre-season training, while the control group (CG) was instructed to perform their originally planned pre-season training.

Subjects

The total sample comprised 46 players aged 15–26 years, where two separate football teams were cluster-randomized to either TG or CG (Table 1). The two teams played at level two and three in Norway, where level two is a national

Table 1 Characteristics of participants

	TG ($n = 24$)	CG ($n = 22$)
Age (years)	18 ± 3	19 ± 2
Body mass (kg)	62 ± 6	63 ± 10
Height (cm)	167 ± 6	168 ± 5
BMI (Kg/m^2)	22.1 ± 2	22.3 ± 3
Experience with the squat exercise		
None	3	8
Some (< 1 year)	14	9
Much (> 1 year)	7	5

Data are mean ± standard deviation. *TG* Training group, *CG* Control group, *BMI* Body mass index league and level three a regional league in Northern Norway. Inclusion criteria was that the players perceived themselves as injury free and able to complete the strength training. Randomization was carried out using the online tool http://www.randomlist.com/team-generator by the first author. Players were only excluded if having injuries that made strength training, running and jumping unachievable. The players carried out~ 6.5 h training per week with their team (Table 2). Four players were injured, two did not complete the required amount of training, one withdrew due to time limitations and five withdrew without providing any reason resulting in 19 participants in TG and 15 in CG that completed both pre- and posttests, and were included in the analyses for training effect (Table 3).

According to the declaration of Helsinki, all participants were fully informed of the potential benefits and risks of the study, both orally and written, before signing an informed consent. For participants under 16 years, both the players and their parents gave their written informed consent. The participants were fully informed of their rights to withdraw from the study at any time without providing any reason. This study was approved by the Norwegian Centre for Research Data for the storage of personal data (Approval reference number: 59063 / 3).

Procedures

All testing and training sessions were conducted in an exercise training laboratory at Alfheim Stadium, Tromsø. Prior to the intervention, the players underwent baseline tests over two test days, with a 72 h washout period to avoid any detrimental effects from the preceding test day: day 1) measurement of body mass and body height, 5-, 10- and 15 m sprint time and a counter-movement jump (CMJ), day 2) 1RM in a free-barbell squat exercise with partial 90° knee angle range of motion (ROM).

Prior to the tests, the participants were asked to refrain from heavy training the preceding day, and to arrive in the laboratory well-hydrated. All tests and training sessions started in the afternoon, with the same general warm-up routine: 7 min of self-selected low intensity cycling on an ergometer bike (Pro/Trainer, Wattbike Ltd., Nottingham, UK) followed by 7 min low intensity running of self-selected speed on artificial grass.

Table 2 Weekly team training for CG and TG prior to inclusion

	CG	TG
Sessions (n)	4–5	4–5
Passing, technique, finishing, possession (min^{-1})	60	270
High intensity small sided games (min^{-1})	90	90
Running and conditioning (min^{-1})	90	45
Strength, balance and injury prevention (min^{-1})	90	0
Stretching (min^{-1})	60	0
Total training time (hours^{-1}: min^{-1})	6:30	6:45

On day 1, following the general warm-up and three 15 m strides on a sprinting field, a 15-m sprint test was carried out. Data were assessed in 5 m splits by photocells mounted to the floor and walls (ATU-X, IC control AB, Stockholm, Sweden) using single-beam electronic barriers. The within-subject coefficient of variation is 2% for this measurement [27]. The surface consisted of artificial grass, and the players wore their own running shoes. The sprints started with the players in a static position placing their front foot 30 cm behind the starting line. A timer was triggered by the participant breaking the initial sensor. The rest interval between the single sprint trials was 180 s [10]. The fastest sprint time of three trials was carried forward for further analyses.

Thereafter, the players rested for 5 min prior to performing the CMJ test [23]. CMJ was assessed by a portable force platform (Hur-Labs, ALU4, Finland), with a validity within 1 cm (2%) when compared with the gold standard mounted floor force platform [28], and a within-subject coefficient of variation of 2.8% [29]. Force data were recorded by a software (Force platform software suite, HURlabs oy, Kokkola, Finland). This device records only the vertical ground reaction force at a sampling frequency of 1200 Hz and jump height is automatically calculated by software applying double integration of the force signal through Simpson's rule of integration. The players were instructed to keep their hands placed on the hips and the feet shoulder-width apart. Each player performed two trials with a ≥ 180 s rest between sets. The highest jump was carried forward for further analysis. Day 1 was ended with a familiarization trial for the squat exercise with low loads.

On day 2, the players returned to the laboratory for the assessment of maximal strength as 1RM. The session was initiated with the same general warm up routine as mentioned above. An Olympic barbell (T-100G; Eleiko, Halmstad, Sweden) and a suitable rack was applied for testing of 1RM. The ~ 90° knee angle of each participant was measured during every repetition using a goniometer, and the players were given an orally "go" when being allowed to start the concentric phase of the lift. Prior to starting their 1RM attempts, the participants warmed up with 10 repetitions with a low load of ~ 50% 1RM (subjectively assessed by the instructor). The starting 1RM attempt was an initial acceptable load decided by the instructor. Each 1RM attempt was carried out by a single repetition, with increasing load of 5–10 kg until they failed to execute the 1RM attempt, which on average was five trials. Each attempt was interspaced by ≥180 s of rest. The within-subject coefficient of variation for squat 1RM is 2.9% [30].

Table 3 Effect of training on body mass, physical performance measures and strength derivatives (Mean ± SD)

Variables	TG ($n = 19$)		CG ($n = 15$)		*P*-value*
	Pre	Post	Pre	Post	
Body mass (kg)	61.67 ± 5.40	62.18 ± 5.31	62.92 ± 10.48	64.09 ± 10.49	0.13
Sprint time (s)					
5 m	1.06 ± 0.05	1.05 ± 0.05	1.06 ± 0.06	1.07 ± 0.06	0.07
10 m	1.89 ± 0.07	1.89 ± 0.08	1.90 ± 0.09	1.90 ± 0.09	0.74
15 m	2.66 ± 0.10	2.64 ± 0.12	2.67 ± 0.13	2.66 ± 0.13	0.51
CMJ Jump Height (cm)	27.32 ± 4.94	27.19 ± 5.93	25.82 ± 5.45	26.12 ± 4.83	0.65
1RM 90° squat (kg)	106 ± 21	137 ± 16	118 ± 28	124 ± 31	0.00
1RM 90° squat (kg/ m_b kg^{-1})	1.73 ± 0.33	2.21 ± 0.32	1.88 ± 0.34	1.94 ± 0.37	0.00
1RM 90° squat (kg/$m_b^{-0.67}$)	6.81 ± 1.29	8.73 ± 1.14	7.45 ± 1.39	7.73 ± 1.52	0.00

TG Training group, *CG* Control group, *CMJ* Counter movement jump, *1RM* 1 repetition maximum. **P*-value represents between subjects effect

Training intervention

The players attended supervised training in the laboratory twice a week for 5 weeks. The training session started with the general warm-up routine described above, before starting the strength training. The program consisted of 90° squats, carried out in the same way as in the 1RM test. The squat training was initiated with three sessions of three sets of six repetitions, followed by seven sessions of four sets of four repetitions. The repetitions were carried out with a slow eccentric movement followed by maximal mobilization in the concentric phase. One hundred eighty second of recovery was given between each set [23]. The load was initially set at 85% of pre-test 1RM, which the participants increased with 2.5–10 kg if they could manage more than six or four repetitions, depending on their scheduled program, resulting in a consistent overload during the whole intervention (Fig. 1). Weight lifted for each repetition was logged continuously during the study. Additionally, for ethical reasons, in order to avoid hamstring strains due to an anticipated large agonist-antagonist strength ratio following the intervention, three sets of six repetitions of the Nordic hamstring exercise were performed after the squat exercise for each session with a ≥ 180 s rest period between sets [31] (Fig. 1).

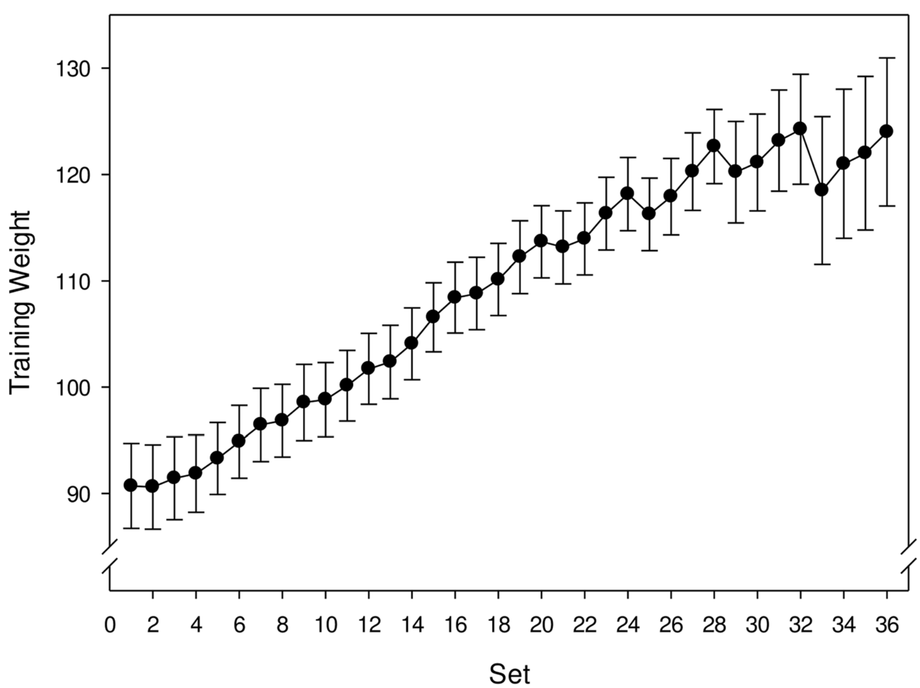

Fig. 1 The logged training for the 90° squat exercise performed as maximal strength training (MST) by the training group. The dots represent the average weight lifted ± SE (vertical bars) during each set

Statistical analyses

All statistical analyses were carried out using the Statistical Package for Social Sciences (SPSS, Version 25, IBM, USA). The Shapiro Wilk test confirmed all data, except for body weight in CG ($p = 0.02$) and 5 m sprint in TG ($p = 0.02$), to not deviate from normal distribution. Data were analysed via a two x two repeated measure analysis of variance (ANOVA). Two levels corresponding to the groups (i.e., TG and CG) are specified as the between-subjects factor. The within-subjects factor (time of test) represents the pre- and post-tests. Effect sizes were calculated as partial eta squared (${}_p\eta^2$) were a small, medium and large effect size was determined as 0.01–0.05, 0.06–0.13 and ≥ 0.14 ${}_p\eta^2$ [32]. All values are presented as mean ± standard deviation (SD). Descriptive values for female football players in 90° squat is reported once (112 kg) [33], where SD is not reported. In one similar study in males where mean 1RM squat strength is 116 kg, the reported SD was 20.1 [23] kg. It is previously reported that a 24% increase in 1RM squat strength results in a 2% improved sprint performance in male football players [8]. Thus, to observe a 24% improvement in strength with 80% power and an alpha level of 0.05, 9 participants are required in each group.

Results

Nineteen participants in the TG and 15 participants in the CG performed all pre and post-tests and ≥ 70% of all training sessions (one subject performed 70%, seven subjects performed 80%, five subjects performed 90% and six subjects performed 100%). The baseline values for the participants included in the intervention analysis were not different between the two groups (Table 3).

There was no main effect of time for 5 m ($p = 0.77$, ${}_p\eta^2 = 0.003$), 10 m ($p = 0.82$, ${}_p\eta^2 = 0.002$) or 15 m ($p = 0.36$, ${}_p\eta^2 = 0.026$) sprint time, and consequently no interaction effects of time x group was observed (5 m: $p = 0.72$, ${}_p\eta^2 = 0.097$, 10 m: $p = 0.74$, ${}_p\eta^2 = 0.003$, 15: $p = 0.51$, ${}_p\eta^2 = 0.014$) (Table 3).

Similarly, no main effect of time for CMJ was observed ($p = 0.87$, ${}_p\eta^2 = 0.001$), and consequently no interaction effect of time x group was observed ($p = 0.65$, ${}_p\eta^2 = 0.006$).

The players increased their 1RM in squats (main of effect of time: $p < 0.00$, ${}_p\eta^2 = 0.704$), and an interaction effect of time x group was observed ($p < 0.00$, ${}_p\eta^2 = 0.516$) where the TG increased their 1RM significantly more than the CT (between subjects effects: $p < 0.001$, ${}_p\eta^2 = 0.965$).

The players increased their body mass ($p < 0.001$, ${}_p\eta^2 = 0.332$), however, no interaction effect between groups was observed ($p = 0.13$, ${}_p\eta^2 = 0.070$) (Fig. 2).

Discussion

In this cluster-randomized controlled trial, 5 weeks of MST improved 1RM, but this maximal strength improvement did not result in any improvements in sprint time or CMJ performance in female football players.

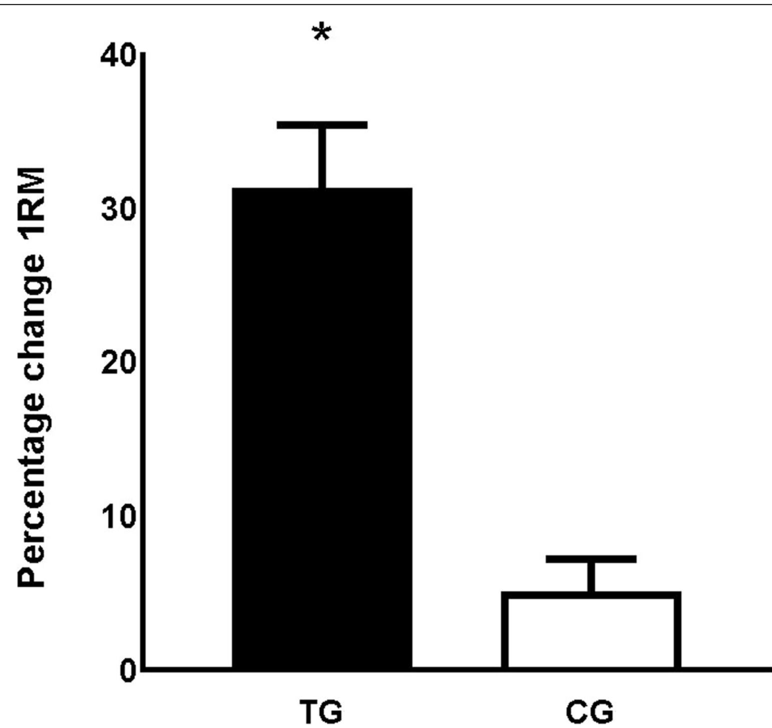

Fig. 2 The mean percentage change from pre- to posttest for 1RM ± SE in TG and CG. TG = training group; CG = control group; 1RM = 1 repetition maximum. * = Between group difference $p < 0.01$

We observed a large increase in absolute 1RM strength of 31 kg (31%) for the TG, being highly superior to the 5% increase in 1RM for the CG. This is a more pronounced increase in strength than observed on average for highly trained male football players [8]. On the one hand, as untrained individuals seem to have greater improvements in strength following ST compared with trained individuals [34], the large improvements in this study may be due to the low experience of ST in the participants of the present study. On the other hand, the baseline values in this study was similar to previously reported values for elite female football players [33], where the present study's participants ended up being considerably stronger than their elite peers (the present study's participants: 137 kg, previously reported values for elite peers: 113 kg). Moreover, following 5 weeks of MST, the participants in our study displayed similar absolute 1RM 90° squat strength (present study: ~ 136 kg) as two previously reported elite male football teams (Male players: ~ 116/ 135 kg,) [15, 23].

Previous studies applying ST in female football players have assessed strength outcomes in isometric [35] or isokinetic exercises [36, 37], making comparisons with the present study unattainable as we measured dynamic squat strength [38]. Elite male football players experienced a 52% increase in absolute 1RM following 16 sessions of MST over 8 weeks [23]. Considering the similar relative increase per training session in the present study (~ 3.6% increase per session) compared with the study by Helgerud et al. [23] (~ 3.2% per session), one may speculate that there are small sex differences in strength improvements following MST in football players. As a linear increase in strength gain has been observed from onset of ST with up to 8 weeks before sign of plateau is observed [39] and duration of our study was 5 weeks, one may speculate whether the players in our study did not reach their expected plateau for strength improvements.

The present study's participants displayed an increase in body mass, which is consistent with earlier findings in men [23]. Considering that both the TG and the CG in the present study performed pre-season training, one explanation for the increased body mass may be an increased water uptake in muscles due to the improved glycogen uptake in muscles [40], which is observed following training initiation [41]. Nevertheless, it is unlikely that the increased body mass solely explains the large increase in 1RM strength in the present study, suggesting a large improvement in neural drive and/or improved motor unit recruitment following the MST intervention [39].

There were no improvements in sprint following MST in this study, which is in contrast to previous findings in male football players [20, 23]. In fact, an average increase of 23.5% increase in 1RM is required for a 2% improvement in 10 m sprint in the males [8]. The previous studies conducted in males employed longer intervention duration compared with this present study [10, 20, 23]. Thus, as there may be a dose-response relationship between improvements in explosive actions and ST training duration [42], the intervention duration may have been too short in the present study [43]. However, there are other possible explanations for the lack of improvement in sprint performance. One may be that the players performed insufficiently amounts of specific sprint training in the pre-season cycle. It is previously shown that in order to improve sports-related high-velocity movements, these movements must be performed in everyday training [44]. Moreover, as football is concurrent sport with need for both endurance and strength, an interference effect could be present for the adaptation to training [45]. Interestingly, the interference effect from concurrent training is shown to be more pronounced for adaptations to power actions, compared with adaptations to strength, meaning that force at high velocities is affected to a larger extent than force at low velocities [46], which could explain the lack of improvement in sprint and jump abilities, although strength was increased.

There were no jump height improvements in the present study, which is consistent with a previous study in females [47], but in contrast to a study conducted with males [8]. Previous studies who observed an increased CMJ jump height in female football players included plyometric training [42, 48–50], thus, as for sprint adaptations, the specificity of training may explain the unimproved jump performance as well [44].

A stronger muscle will tolerate a higher force, making it more resistant to injury. Although not measured in the current study, ST reduces injury rate, and shortens rehabilitation time [51]. Moreover, the strength of connective tissues and joint stability is also improved after ST [52]. That is of particular importance in the female football player population as they have a two to six times greater prevalence of anterior cruciate ligament injuries compared to their male equivalents [53]. The players in the present study showed similar body mass values as their national level peers [53], which is suggested as optimal for physical performance for female football players [54]. Moreover, as age, anthropometry and physical variables did not differ between the two teams in the present study, comparisons were regarded as appropriate. Finally, although performance by means of sprint speed or jump height was unchanged in the current study, an increased strength could potentially improve performance through pathways not assessed in this paper. For example, this could lead way for future studies with higher ecological value, where the assessment of fatigue delay, technical actions and number of interceptions during match play could be studied following such a large increase in strength. MST has mainly been evaluated in male athletes, and this study is to our knowledge the first to investigate the effect of MST for dynamic strength 1RM, sprint speed and jump height in female football players.

There are several limitations of this study. First only six of the participants accomplished 100% of the training, which means that the other participants had some weeks when they only performed one ST session. Moreover, the CG was instructed to continue their habitual training, without any substitute for the added training time seen in the TG during the intervention. Thus, we are not able to distinguish between the effect of MST and the effect of an added training volume per se.

Although the participants in this study played at senior level football, their mean age was ~ 18 years, which can be considered junior level age. In contrast, those who are competing at the national level and in the highest level domestic leagues in other countries, are typically between 20 and 27 years [53]. Thus, although the participants in the present study aim at competing at the highest level possible, they may not be at the peak of their performance level at the present age. Secondly, we propose improved neural adaptations as the main mechanism driving the observed increase in 1RM. However, more sophisticated measurement methods are required to assess which type of neural adaptations that are responsible for this increase.

Conclusions

MST improves maximal strength in female football players; however, the improvement in maximal strength did not result in any transference to improvements in sprint speed or jump height in this study. This indicates that female football players may need to incorporate specific sprint and jump training into their weekly training routines in order experience improvements in sprint and jump performance. However, our intervention was only 5 weeks, hence, it is unknown whether a longer intervention period would allowed these players to improve their sprint and jump performance, as it is observed previously for male players.

Abbreviations

1RM: 1 Repetition maximum; CG: Control group; CMJ: Counter movement jump; MST: Maximal strength training; TG: Training group

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Authors' contributions

SP: In charge of writing, training, statistics, study design and data collection. ES and KH: training, data collection and manuscript writing. SAP: Study design and manuscript writing. DJ: Manuscript writing. All Authors read and approved the final manuscript.

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Availability of data and materials

Trial protocol and the datasets used in in the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

According to the declaration of Helsinki, all participants were fully informed of the potential benefits and risks of the study, both orally and written, before signing an informed consent. For participants under 16 years, both the players and their parents gave their written informed consent. The participants were fully informed of their rights to withdraw from the study at any time without providing any reason. This study was approved by the Norwegian Centre for Research Data for the storage of personal data (Approval reference number: 59063 / 3). The study adheres to CONSORT guidelines.

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

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Publisher's Note

Paper III

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Flywheel squats versus free weight high load squats for improving high velocity movements in football. A randomized controlled trial

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RESEARCH ARTICLE Open Access

Flywheel squats versus free weight high load squats for improving high velocity movements in football. A randomized controlled trial

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Abstract

Background: High load (HL: > 85% of one repetition maximum (1RM)) squats with maximal intended velocity contractions (MIVC) combined with football sessions can be considered a relevant and time-efficient practice for maintaining and improving high velocity movements in football. Flywheel (FW) resistance exercise (RE) have recently emerged with promising results on physical parameters associated with football performance.

Methods: In this randomized controlled trial over 6 weeks, 38 recreationally active male football players randomly performed RE with MIVCs two times per week as either 1) FW squats ($n = 13$) or 2) barbell free weight (BFW) HL squats ($n = 13$), where a third group served as controls ($n = 12$). All three groups conducted 2–3 football sessions and one friendly match a week during the intervention period. Pre- to post changes in 10-m sprint, countermovement jump (CMJ) and 1RM partial squat were assessed with univariate analyses of variance.

Results: The FW and BFW group equally improved their 10-m sprint time (2 and 2%, respectively, within group: both $p < 0.001$) and jump height (9 and 8%, respectively, within group: both $p < 0.001$), which was superior to the control group's change (between groups: both $p < 0.001$). The BFW group experienced a larger increase (46%) in maximal squat strength than the FW group (17%, between groups: $p < 0.001$), which both were higher than the control group's change (both $p < 0.001$).

Conclusion: Squats carried out with FWs or BFWs where both are performed with MIVCs and combined with football sessions, were equally effective in improving sprint time and jump height in football players. The BFW group experienced a more than two-fold larger increase in maximal partial squat strength than the FW group in maximal partial squat strength. This presents FW RE as an alternative to BFW HL RE for improving high velocity movements in football.

Trial registration: ClinicalTrials.gov Identifier: NCT04113031 (retrospectively registered, date: 02.10.2019).

Keywords: male1, soccer2, Maximal strength3, sprint4, jump5, power6

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Background

Maximal and high velocity forces are considered decisive for human movement performance. In modern football, the importance of performing rapid and high velocity movements, such as sprints and jumps, has gradually increased [1–5]. Maximal lower limb muscle strength is associated with lower limb muscle power [6, 7], where an increase in lower limb muscle strength is likely to result in an increased sprint performance [8].

High power resistance exercise (RE) with high velocities and low external loads is effective for improving rapid and high velocity movements [8–11]. However, independent of external loads, the intention of maximal velocity while performing RE is likely the most prominent factor for increasing the neural drive to the muscles, resulting in an increased velocity in the mechanical response [8, 12–14]. This is likely explained by short time to peak tensions, high rates of torque development, high motor unit discharge rates and an early and fast motor unit recruitment [15–18]. Consequently, RE with high external loads (HL: ≥85% of 1RM) and subsequently low velocity movement is also likely effective, as long as the intended velocity during the contractions is maximal [13]. In fact, HL RE is reported to be effective in football players when it is combined with performing high velocity movements (e.g. sprints and jumps) in football practice [8, 19]. Additionally, although the intensity in HL RE is high, the low number of repetitions and sets allows the total RE volume to be low. Due to the challenges of incorporating all important physical aspects while also ensuring sufficient recovery time in football players' weekly exercise and competitive schedules [20], HL RE can be considered a relevant and time-efficient exercise modality for maintaining [21] and improving [22, 23] sprint and jump performance in football.

As eccentric muscle contractions allows for higher force production compared to the concentric contractions [24, 25], exercises with eccentric overload, such as inertia spinning YoYo™ flywheel (FW) devices [26], have been suggested as an alternative or supplement to the established exercise modalities [24, 25]. In FW devices, a band is connected to a pivoting shaft, where pulling the band unwinds the band and kinetic energy is subsequently produced in the shaft due to the inertia of the spinning FW. When the band reaches its maximal length, the FW keeps spinning and rewinds the band again and high muscle force is produced during the eccentric phase if the individual is trying to slow the spinning of the FW, where peak muscles forces are produced if the individual is instructed to break the eccentric movement towards the end of the rewound band [26, 27].

Over the past two decades, a substantial number of studies have assessed the utility of FW RE for improving sports performance, with positive effects on maximal strength, muscle power, jump height, sprint performance and changes of direction movements [26, 27]. Although the evidence for improved performance is compelling, there are fewer studies comparing FW RE to other RE modalities, which is necessary to determine whether FW exercise could have similar effects compared with the established RE modalities.

To our knowledge, no study has compared the effect of FW RE versus free weight RE using the same motion path, which consequently stimulates the same muscles. Additionally, no study has compared the effect of FW exercise and free weight using HL with maximal intended velocity contraction (MIVC)s combined with football sessions, which can be considered a relevant and time-efficient exercise modality for improving high velocity movements in football while also improving maximal strength [22, 23]. Such information can be highly applicable for coaches in football clubs, who should use the best practice in relation to total exercise load to optimize performance of the players, at least in elite clubs. Thus, the objective of this study was to compare the effect of FW RE versus free weight HL RE on 10-m sprint time, countermovement jump (CMJ), and 1RM partial 90° range of motion (ROM) squat strength in football players. In this randomized controlled trial, both the FW RE and the free weight RE were carried out in a squat exercise with MIVCs and combined with football sessions. We hypothesized 1) that RE using FW and barbell free weight (BFW) combined with football practices will equally improve sprint time and jump height, and 2) that squats carried out in a BFW exercise will result in superior improvements in 1RM partial squat compared with FW squats.

Methods

Design

In this randomized controlled trial, we randomly allocated 49 players into three different groups using Research Randomizer [28] (three sets, 17 numbers per set, ID-number range 1–49, *"every number unique"*, *"no sorted order"* and *"no place marker"*); 1) flywheel (FW) group ($n = 16$), 2) barbell free weight (BFW) group ($n = 16$) and 3) control group ($n = 17$). Due to drop out (22.5%), the final number in the three groups were 13, 13 and 12 players in the FW, BFW and control group, respectively. The FW and the BFW group participated in an intervention where they performed a squat exercise either with a FW device or with BFWs twice a week over 6 weeks (in total 12 sessions) as part of their preseason preparations. The control group was instructed not to perform lower body RE and only to perform their teams' preseason preparations and acted as controls. During the intervention period, all enrolled players were instructed to avoid complementary REs for their lower body, while no restrictions were given regarding REs for their upper body. Our outcome measures were 10-m sprint time, CMJ and 1RM partial squat, which we measured pre- and post the 6 week long intervention.

This study was carried out in accordance to the Declaration of Helsinki; prior to pre-tests, all the players were informed of the purpose of the study and its associated risks and benefits, before providing oral and written informed consent. The Norwegian Data Protection Service approved the study and the storage of personal data (Approval reference number: 374030), without further Regional Ethical approval per applicable institutional and national guidelines for sport and exercise science [29, 30].

Subjects

In the pre-season period in Norway, from January to March 2019, 49 recreationally active football players volunteered to participate. Recruitment period was January 5th to January 31st, data collection was from February 1st to March 31st. The players played at the two highest regional levels in the Norwegian national league system, which is the 5th and 6th levels in Norway. After contacting multiple 5th and 6th level teams' coaches, the included players were recruited from teams with similar overall exercise load with the following inclusion criteria; 1) two or three 60 min football sessions and 2) one friendly football match a week. Exclusion criteria was no injury or disease preventing from participation in RE and football practice. The flow and random allocation of participants are illustrated in Fig. 1. Four of the 49 recruited players reported to be unfamiliar with RE, while the remaining players reported to perform 1–6 weekly RE sessions beside their teams' football sessions. Four players withdrew from the study prior to study completion due to illness and injuries not related to the study interventions, and seven players did not show up for post-tests. As a result, 38 players completed the study. The descriptive baseline test characteristics are shown in Table 1; there were no differences in baseline characteristics between the intervention groups (all $p \geq 0.20$).

Test procedures

Prior to the interventions, the players underwent pre-tests in the following order on the same test day: 1) 10-m sprint time, 2) CMJ and 3) 1RM in a barbell free weight partial squat, carried out as 90° ROM in the knee joint (standing position = 180°). The players' height was assessed on a portable scale (Seca 217, Seca GmbH & Co., KG, Germany) and body mass on a portable force platform (Hurlab FP4, HUR Labs Oy, Kokkola, Finland), which was connected to a portable laptop (ThinkPad, Lenovo Group Ltd., Beijing, China) through a USB cable and monitored with the manufacturer's software (Force platform software suite, HUR Labs Oy, Kokkola, Finland). Body mass index (BMI) was calculated. Prior to testing, the players jogged for 15 min at progressively increasing intensity (easy to moderately paced jogging) with various exercises (e.g. knee raises, heel kicks, lunges, and frontal vertical kicks to their hands) on artificial grass, supervised by an instructor. The subjects wore jogging shoes and light clothing. Following the 15 min jog, the players performed two

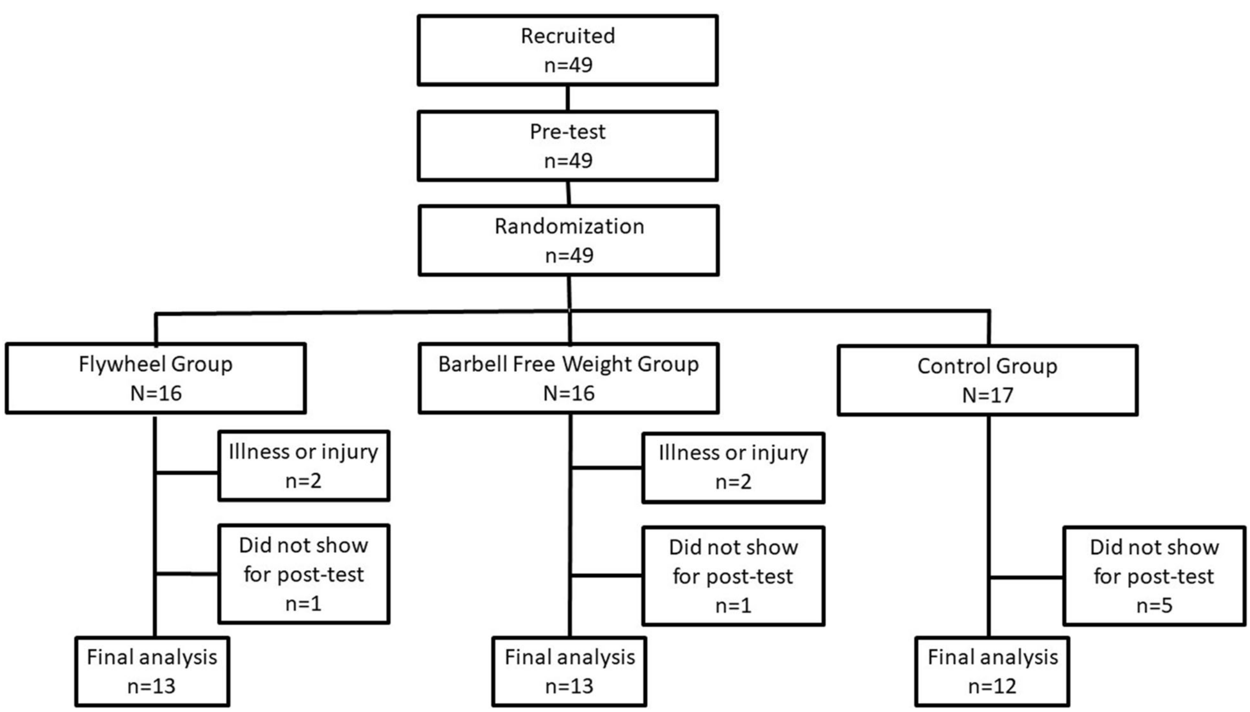

Fig. 1 The flow and random allocation of participants

Table 1 Baseline descriptive characteristics of the football players expressed by group

	FW group (n = 13)	BFW group (n = 13)	Control group (n = 12)
Age (yr)	23.07 ± 3.15	23.23 ± 2.12	25.3 ± 2.39
Body mass (kg)	78.69 ± 7.42	78.87 ± 11.98	83.13 ± 7.06
Height (m)	1.81 ± 0.05	1.81 ± 0.05	1.82 ± 0.04
BMI (kg/m^2)	24.08 ± 1.85	24.22 ± 2.44	25.21 ± 1.70
RE volume per week (hr)	2.3 ± 1.50	3.0 ± 2.13	2.3 ± 1.78
Playing Level			
Fifth level (n)	12	13	10
Sixth level (n)	4	3	2
Playing position			
Goal Keeper (n)	2	1	N/A
Central back (n)	4	3	3
Full back (n)	3	2	4
Central midfielder (n)	4	4	5
Wide midfielder (n)	3	3	2
Striker (n)	1	3	2

Data are shown as mean ± SD. *FW* Flywheel, *BFW* Barbell free weight, *RE* Resistance exercise, *BMI* Body mass index

progressive 15-m sprints instructed to be at 95% of self-determined maximum acceleration.

10-m sprint test

The 10-m sprint test was performed on artificial grass indoors. Single-beam photocells (ATU-X, IC Control AB, Stockholm, Sweden), mounted to the floor and walls recorded the sprint times, where the photocells at the starting and the finishing line were placed 20 cm and 100 cm above the ground, respectively. Within-subject coefficient of variation of single-beam photocells is reported to be 2% [31]. A marker was placed 30 cm behind the starting timing gate, where the players chose their starting position behind the marker. The players started the test on their own initiative, and without verbal encouragement, by breaking the laser beam at the starting timing gate and sprinted to the finishing line as fast as they could. Each player was given three attempts with 3 min recovery between each sprint. The fastest sprint time was recorded.

Countermovement jump

Following ≥3 min rest from the sprint test, the players performed the CMJ test on the portable force platform (Hurlab FP4, HUR Labs Oy, Kokkola, Finland) following the body mass measurement. Portable force platforms is found to measure CMJ jump height within a 2% accuracy compared to a laboratory floor mounted force platform (Type 9281B Kistler, Instrumente AG, Winterthur, Switzerland) [32] and with a 2.8% within-subject coefficient of variation [33]. Starting from an upright standing position with their feet shoulder-width apart and with both hands placed on their hips, the players were instructed to make a preliminary downward movement (eccentric phase) by flexing their knees to approximately 90° (knee-flexion) before performing the concentric phase of the vertical jump off the ground by extending the knees and the hips, respectively. Each player was given three attempts with 3 min recovery between each jump. If an incorrect jump was performed (e.g. typical mistake was lifting the heel prior to extending the knees), the player was given a new attempt. The force platform measures the vertical jump height in centimetres (cm) by calculating the centre of mass displacement from force development (take-off velocity) and body mass. The sampling rate was set to 1200 Hz. The highest vertical jump was recorded.

One repetition maximum in partial squat

Following the CMJ test, the players performed a partial ROM (approximately 90° knee joint angle) back squat test using an Olympic barbell (Eleiko, Halmstad, Sweden) for the assessment of 1RM. We used a slightly modified 1RM protocol used by Helgerud et al. [34]. The players first warmed up by lifting the Olympic barbell (20 kg) without additional weights for 8–10 repetitions, and thereafter performing two sets of progressively decreasing repetitions (6 and 3 repetitions, respectively) and increasing the weights based on their perceived effort in the previous warm-up set (Helgerud et al. [34] specified no 1RM warm up). Thereafter, the players attempted their 1RM trials with increasing weights (10 kg) until failure (Helgerud et al. [34] used 5 kg increments). Failure was defined as inability to lift the barbell to standing (starting) position (180° knee joint angle). A mechanical goniometer was held to the lateral part of their knee joint by an instructor to ensure that the players reached 90° of knee flexion before they were given a verbal "go" and they could start the concentric phase of the lift. The kilograms (kg) lifted in the last approved lift with one repetition was considered their 1RM and recorded in kg. One repetition maximum was normally reached between 3 and 6 sets, ≥3 min recovery was given between each attempt. The coefficient of variation for 1RM squat is reported to be 2.9% [35]. As 1RM strength divided by body mass may be imprecise where a heavier individual may be overestimated and a lighter individual underestimated [34, 36], the kg lifted was also allometrically scaled as kg lifted in the squat exercise multiplied by body mass raised to the power of 0.67 (kg lifted·kg body mass$^{-0.67}$) [34, 36].

Exercise interventions

An overview of the exercise programs is presented in Table 2. Over the course of the interventions, all players in all three groups were instructed to adhere to their two-three weekly football sessions and friendly matches of their team. The players in the FW and BFW groups started their RE interventions the week following pre-tests, which did not coincide with their football sessions (i.e. RE and football sessions was separate). Prior to both intervention groups' sessions, the players performed a 10 min self-selected low intensity aerobic warm-up on a motorized treadmill (ELG 70, Woodway Inc., Waukesha,Wisconsin, United States) or an ergometer bike (Pro/Trainer, Wattbike Ltd., Nottingham, United Kingdom). For both groups, the players were instructed to perform their exercise with MIVCs and were given verbal encouragement throughout the sessions. All intervention sessions were performed in the same laboratory and supervised by the same instructor. The players in both intervention groups were expected to experience a large increase in knee extensor strength. Therefore, the players performed the Nordic hamstring exercise to avoid a large quadriceps-to-hamstring strength ratio and thereby potentially reduce the risk for hamstring strains [37].

The Nordic hamstring exercise was performed at the end of each exercise session (for both interventions) and involved three sets of four repetitions (week 1) where the number of repetitions were progressively increased to five in week 2, six in week 3–4, eight in week 5, and 10 in the final week of the interventions. At the end of the 6-week exercise interventions, the participants performed post-tests in the same order as the pre-tests.

Table 2 The exercise programs of the interventions

	Flywheel group	Barbell Free Weight group	Control Group
Equipment	Flywheel Device	Olympic Barbell, free weight and squat rack.	N/A
Exercise sets and repetitions (intensity)			
Week 1 (Familiarization sessions)			
Intervention exercise	3 × 6 (inertia #1, #2, #3 or #4)	3 × 8 (~ 70% of 1RM)	N/A
Nordic Hamstring	3 × 4 (Body weight)	3 × 4 (Body weight)	N/A
Week 2			
Criteria for increasing load	*An average > 4 watts·kg^{-1} from each repetition of one set*	*If they could perform five repetitions within one set*	*N/A*
Intervention exercise	3 × 6 (inertia #1, #2, #3 or #4)	4 × 4 (> 85% of 1RM)	N/A
Nordic Hamstring	3 × 5	3 × 5 (Body weight)	N/A
Week 3			
Intervention exercise	3 × 5 (inertia #1, #2, #3 or #4)	4 × 4 (> 85% of 1RM)	N/A
Nordic Hamstring	3 × 6 (Body weight)	3 × 6 (Body weight)	N/A
Week 4			
Intervention exercise	4 × 5 (inertia #1, #2, #3 or #4)	4 × 4 (> 85% of 1RM)	N/A
Nordic Hamstring	3 × 6 (Body weight)	3 × 6 (Body weight)	N/A
Week 5			
Intervention exercise	4 × 4 (inertia #1, #2, #3 or #4)	4 × 4 (> 85% of 1RM)	N/A
Nordic Hamstring	3 × 8 (Body weight)	3 × 8 (Body weight)	N/A
Week 6			
Intervention exercise	4 × 4 (inertia #1, #2, #3 or #4)	4 × 4 (> 85% of 1RM)	N/A
Nordic Hamstring	3 × 10 (Body weight)	3 × 10 (Body weight)	N/A

N/A Not applicable. Inertia #1 = 0.025 kg·m^{-2}, #2 = 0.05 kg·m^{-2}, #3 = 0.075 kg·m^{-2} or #4 = 0.1 kg·m^{-2}

Flywheel squat group

The players allocated to the FW group was equipped with a vest on their upper body connected with a band to the FW device (#215 YoYo Squat Unlimited Pro, nHance, YOYO Technology, Stockholm, Sweden). In the FW device, different sized spinning inertia FWs can be connected to the pivoting shaft (size #0.5: 0.0125 kg·m^{-2}, #1: 0.025 kg·m^{-2}, 2#: 0.05 kg·m^{-2}, 4#: 0.1 kg·m^{-2}). The first two sessions (week 1) were familiarization sessions, which consisted of three sets with six repetitions. Thereafter, from week 2, the players performed three sets with six repetitions with MIVCs followed by 3 × 5, 4 × 5 and 4 × 4 repetitions in week 3, 4 and 5–6, respectively. Recovery time between sets was set to ≥3 min. The players started in a partial squat position (~ 90° knee angle) and performed first a standardized warm-up set with six repetitions using the #1 inertia FW (0.025 kg·m^{-2}). In all exercise sets, the players started with three slow repetitions to get into the flow of the squat exercise movement before beginning their scheduled MIVC sets (6 × 3, 5 × 3, 4 × 5, 4 × 4 depending on exercise week), where they were given a verbal "go" when starting to push with MIVCs from starting position (~ 90° knee joint angle) to standing position. The band connecting the vest and the FW device was strapped tightly making the players stop at approximately 175° knee joint angle in the standing position when the FW band was unwound. When the FW continued to rewind again, this immediately forced the player to bend their knees and begin the eccentric contraction phase of the next repetition. The players were instructed to over-win the kinetic energy with the highest possible mobilization of muscular force at the end of the eccentric movement (~ 80° knee joint angle), and immediately start a new concentric MIVC. During the sets and sessions, the load (Watt) was monitored using the manufacturer's application (Bluebrain, Kuopio, Finland) on a portable tablet (Samsung Galaxy S4, Samsung Electronics, Daegu, South Korea) connected to the FW device through Bluetooth. The starting inertia at week 2 was set to #1 (0.025 kg·m^{-2}). If the players produced on average > 4 watts·kg^{-1} from each repetition of one set, the FW size was increased, to #2 (0.05 kg·m^{-2}) and later to "#3" (#1 + #2 = 0.075 kg·m^{-2}) and finally #4 (0.1 kg·m^{-2}).

Barbell free weight squat group

The players in the BFW group performed a specialized warm-up with three sets of progressively increasing intensity in the squat exercise; eight repetitions at 30%-, six repetitions at 50%- and six repetitions at 70% of 1RM, respectively. The first two sessions (week 1) consisted of three sets with eight repetitions at ~ 70% of 1RM. Thereafter, from the third session (week 2), the players were instructed to perform four sets of four repetitions at > 85% of 1RM throughout the remaining sessions with progressively increasing the load with 5 kg if they could perform five repetitions within one set (e.g. if performing 5 repetitions, the load in the next set was increased, which could be set 1, 2, 3 or 4 in the exercise session). Recovery time between sets was set to ≥3 min. Figure 2 illustrates the logged progression of the BFW group.

Statistical analyses

The Shapiro Wilk test confirmed all data to not deviate from normal distribution, both prior (all $p \geq 0.11$) and following randomization (all $p \geq 0.052$), which were confirmed by inspection of the Q-Q plots. We performed paired sample t-tests to assess pre- to post-test changes within groups. One-way univariate analyses of variance (ANOVAs) with Bonferroni corrected post-hoc tests were used to examine differences in baseline characteristics, and in the change score (post-pre) from pre-to post-test between the groups. Effect sizes were calculated as Cohen's d where determination of magnitude was considered according to Rhea's recommendation for RE interventions of moderately fit individuals; trivial: < 0.35, small: 0.35–0.79, medium: 0.80–1.49, large: ≥1.50 [38]. For pre- to post effect size within groups, we divided the mean change score by the standard deviation (SD) of the change score. We calculated between groups effect size by the pooled SD of the two groups of interest (e.g. FW vs BFW, FW vs control, BFW vs control) divided by the difference in mean change score of the two groups of interest using the following formula:

$$\sqrt{\frac{(n_1 = 1) \times SD_{1^2} + (n_2 - 1) \times SD_{2^2}}{n_1 + n_2 - 2}} / m_1 - m_2$$

Where n_1 and n_2 represents the groups' n, SD_1^2 and SD_2^2 represents the groups' SD squared, m_1 and m_2 represents the two groups' mean change score, respectively. We used Pearson's correlations to assess the association between the change in sprint time and jump height, respectively, and the change in maximal partial squat strength. We adopted linear regressions to assess whether inclusion of changes in body mass could explain more of the variation in the association than maximal partial squat change alone. We performed a pilot study where we observed a mean decrease of 0.0243 ± (SD) 0.0215 s in the 10-m sprint test following 6 weeks of partial squat exercise at > 85% of 1RM characterized by 4 × 4 repetitions. Sprinting 0.02 m·s^{-1} faster over 10 m would result in a ~ 10 cm difference, which can be considered a shoulder length ahead of an opponent and thus a game changing and relevant difference [14]. With 80% power and an alpha level of 0.05, we calculated to need 12 participants in each group. We assumed a 25%

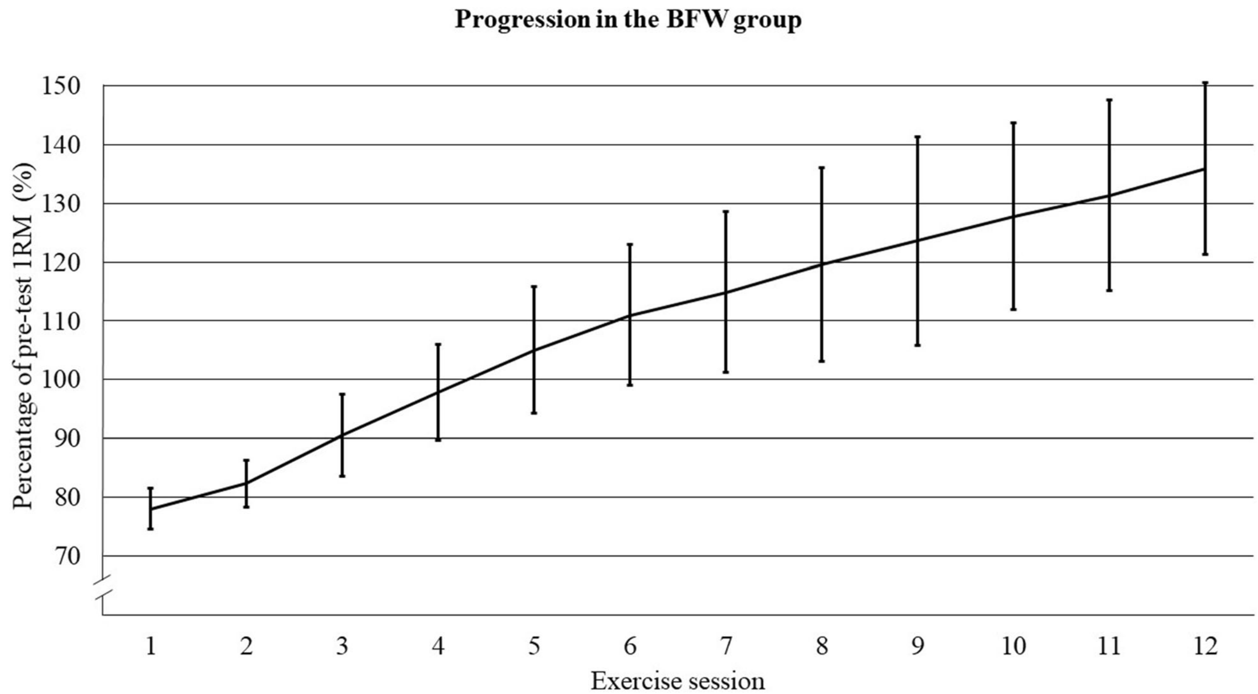

Fig. 2 The logged progression of the players in the BFW group. Data are percentage of pre-test 1RM lifted in the final set of the session and shown as mean with error bars as SD. BFW = barbell free weight, 1RM = one repetition maximum, SD = standard deviation

dropout and thus aimed to recruit at least 45 participants (15 in each group); following dropouts (22.5%), we ended up with 13 (FW), 13 (BFW) and 12 (control) in our three groups for the final analyses. Data are shown as mean ± SD unless otherwise is stated. All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS, Version 26, IBM, Armonk, NY, United States).

Results

The pre- and post-test results are presented in Table 3. There were differences in changes in the 10-m sprint test between the groups (between subjects effect: $p < 0.001$), where the FW and the BFW group equally decreased their 10-m sprinting time from pre- to post-test by 2% (between groups: $p = 1.00$, Cohen's *d:* 0.00, pre- to post-test: FW group: $p < 0.001$, Cohen's *d*: – 0.97; BFW group: $p = 0.005$, Cohen's *d*: – 0.96), while the control group did not decrease their sprinting time ($p = 0.39$, Cohen's *d*: 0.26; difference between FW and BFW vs control: both $p < 0.001$, both Cohen's *d:* – 1.39) (Table 3). The individual change in 10-m sprint time from pre- to post-test and the association with 1RM partial squat change is illustrated in Fig. 3. Two out of the 13 in the FW group did not experience a game changing relevant change in 10-m sprint performance (≥0.02 s decrease in 10-m sprint time; range FW group: 0.02 to – 0.08 s, mean increase: – 0.03 ± 0.01 s). Four out of the 13 in the BFW group (range: – 0.01 to – 0.04 s, mean increase: – 0.03 ± 0.03 s) and 11 out of the 12 players in the control

Table 3 Pre- and post-test results

	FW group (n = 13)		BFW group (n = 13)		Control group (n = 12)	
	Pre-test	Post-test	Pre-test	Post-test	Pre-test	Post-test
Body mass (kg)	78.69 ± 7.42	79.33 ± 7.29	78.87 ± 11.98	79.33 ± 12.19	83.13 ± 7.06	83.20 ± 6.68
10 m sprint time (s)	1.75 ± 0.07	1.72 ± 0.07¤*	1.74 ± 0.08	1.71 ± 0.07¤*	1.73 ± 0.04	1.73 ± 0.04
CMJ (cm)	34.38 ± 2.15	37.45 ± 3.46¤*	36.98 ± 3.98	39.75 ± 4.14¤*	35.99 ± 3.79	36.06 ± 3.41
Squat 1RM (kg)	127.69 ± 21.27	149.23 ± 22.16¤*	134.62 ± 26.96	196.92 ± 26.89¤*#	137.50 ± 21.79	140.83 ± 25.39
Squat 1RM scaled (1RM kg·weight $kg^{-0.67}$)	95.27 ± 15.47	111.30 ± 16.01¤*	100.41 ± 19.49	146.94 ± 19.65¤*#	102.23 ± 15.87	104.69 ± 18.50

Data are shown as mean ± SD. ¤significant difference from pre- to post-test, $p < 0.001$, *significant difference in the pre- to post-test change from the control group, $p < 0.001$, #significant difference in the pre- to post-test change from the FW group, $p < 0.001$. *FW* Flywheel, *BFW* Barbell free weight, *CMJ* Countermovement jump, *1RM* One repetition maximum group (0.02 to − 0.02 s, mean increase: 0.003 ± 0.01 s) did not experience a game changing relevant change in 10-m sprint time (Fig. 3).

There were differences in changes in the CMJ test between the groups (between subjects effect: $p < 0.001$), where the FW and the BFW group equally increased their jump height in the CMJ test from pre- to post-test by 9 and 8%, respectively (between groups: $p = 1.00$ Cohen's *d:* − 0.16; pre-to post-test: FW: $p < 0.001$, Cohen's *d:* 1.70; BFW: $p < 0.001$, Cohen's *d:* 1.54), while the control group did not increase their jump height ($p = 0.75$, Cohen's *d:* 0.09; difference between FW and BFW vs control: both $p < 0.001$, Cohen's *d:* FW vs control: 2.15, BFW vs control: 1.94) (Table 3). The individual CMJ change from pre-to post-test and the association with 1RM partial squat change is illustrated in Fig. 4. All players in FW group experienced an increase in jump height (range 0.37–7.01 cm, mean increase: 3.07 ± 1.80 cm). In the BFW group, 11 out of the 13 increased their jump height (range: − 0.43 to 6.10 cm, mean increase: 2.78 ± 1.80), while seven out of the 12 players in the control group experienced an increased jump height from pre- to post-test (range: − 1.64-1.02 cm, mean increase: 0.07 ± 0.72 cm) (Fig. 4).

There were differences in changes in the 1RM partial squat test between the groups (between subject effect: $p < 0.001$), where the BFW group increased their 1RM squat by 46%, which is more than the FW group's increase of 17% (difference between groups: $p < 0.001$, Cohen's *d:* 3.43, pre- to post-test: FW: $p = 0.001$, Cohen's *d:* 3.13, BFW: $p < 0.001$, Cohen's *d:* 3.17), and the BFW and the FW group increased their 1RM squat more than the control group (difference between FW and BFW vs control: both $p < 0.001$, Cohen´s *d*: FW vs control: 2.71, BFW vs control: 4.93, pre-to post-test control group: $p = 0.10$, Cohen's *d:* 0.51). When scaling 1RM partial squat strength to the power of 0.67, the results remained unchanged (Table 3). For individual pre- to post 1RM partial squat changes, all players in FW and BFW group increased their 1RM (FW: range: 10–30 kg, mean increase: 21.5 ± 6.9 kg; BFW: 40–90 kg, mean increase: 62.3 ± 15.4), while three out of the 12 players in the control group increased their 1RM (range: 0–20 kg, mean increase: 0.07 ± 0.72 cm) (Figs. 3 and 4).

We observed a negative linear association between the change in maximal partial squat strength and the change in sprint time (1RM: $r = 0.39$, $r^2 = 0.15$, $p = 0.02$) (Fig. 3). We observed a positive linear association between

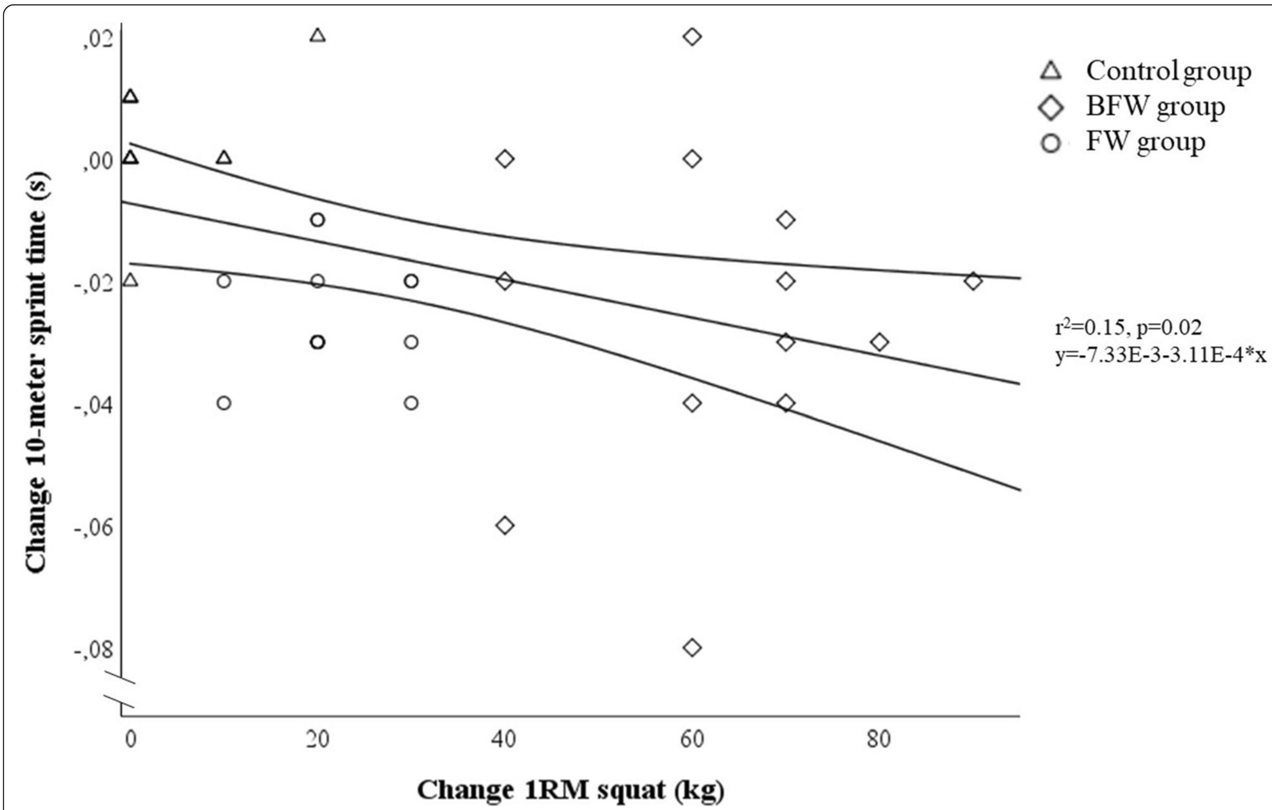

Fig. 3 Scatter plot with regression line and 95% confidence intervals of the pre- to post change in 1RM partial squat strength and 10-m sprint time. The bold triangles, squares and circles indicate multiple data points (multiple individuals having the same values). 1RM = one repetition maximum

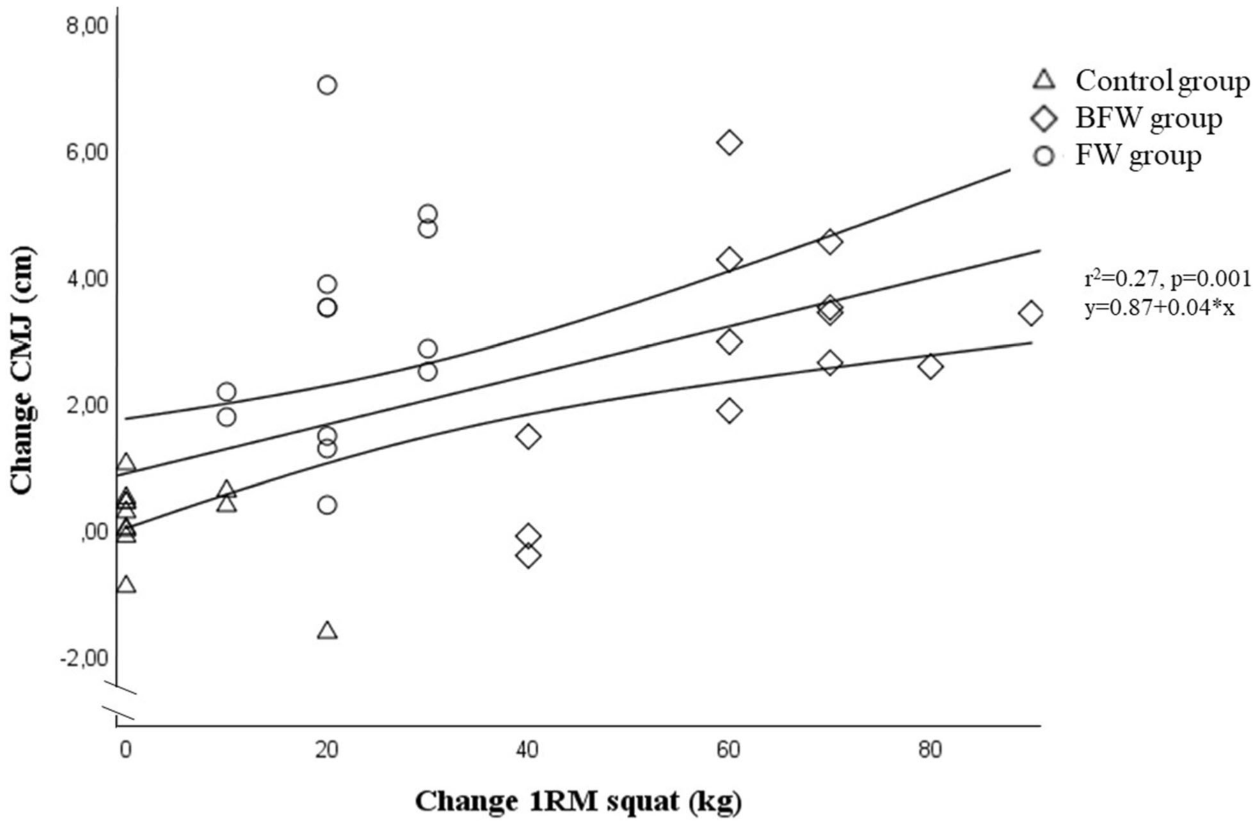

Fig. 4 Scatter plot with regression line and 95% confidence intervals of the pre- to post change in 1RM partial squat strength and CMJ. The bold triangles, squares and circles indicate multiple data points (multiple individuals having the same values). 1RM = one repetition maximum, CMJ = countermovement jump

maximal partial squat strength and jump height (r = 0.52, r^2 = 0.27, p = 0.001) (Fig. 4). These associations were unchanged when including change in body mass as independent variable, and when changing 1RM to scaled 1RM (data not shown).

Discussion

In this randomized controlled trial of recreationally active football players, FW and BFW HL squats equally improved 10-m sprinting time and CMJ height while BFW HL squats was superior to FW squats in improving maximal partial squat strength. Finally, we observed linear associations between changes in maximal partial squat strength and changes in 10-m sprinting time and CMJ, respectively.

The equal improvement for both intervention groups in 10-m sprint time and jump height is in line with the latest systematic review assessing the effect of RE in football players [8], and also with previous studies assessing the effect of BFW HL partial squats combined with football sessions [22, 34]. Although not always consistent [39], sprint improvements following FW squats is reported previously [40, 41], while improvements in jump height following FW RE seem to be a consistent observation [39–41].

Although we observed linear associations between improvements in maximal squat strength and improvements in sprint time and jump height, which is in line with the latest review on the effect of RE in football players [8], the explained variances are low (10-m sprint change: 15% (r^2 = 0.15), Fig. 3; CMJ change: 27% (r^2 = 0.27), Fig. 4), indicating that other factors than increased maximal squat strength may explain the improved 10-m sprint and jump performance. These similar improvements between the BFW and FW groups are likely explained by neuromuscular adaptations induced by MIVCs [12]. For example, using novel high density surface electromyography recordings, a recent study showed an increased motor unit discharge rate accompanied by a decreased motor unit recruitment threshold following 4 weeks of isometric MIVCs [42]. Moreover, it seems that peak rate of force development is associated with peak motor unit discharge rate, which also seem to be generated prior to maximal force development [16], which thus seem to explain the underlying neural mechanisms for improvements of high velocity movements following RE [12].

However, it is reported that neural adaptations preliminary occurs within the first 1–2 weeks of RE [25, 43]. Thus, although the strength of the associations between change in sprint time or jump height and change in maximal squat strength were unchanged when including body mass change as independent variable, we cannot rule out whether our 6 week long intervention induced morphological changes (e.g. increase in pennation angle, fascicle length and cross-sectional area), which normally occur as a result of longer exercise programs. For example, a previous study assessing the effect of FW RE revealed changes in muscle fascicle length and pennation angle, which was paralleled with hypertrophy gains [44].

The BFW group experienced a more than two-fold larger increase in 1RM squat (46%) than the FW group (17%). The 17% increase in the FW group is in line with previous reported increases following squat RE in football players [8], while the 46% increase in the BFW group is towards the highest reported increases in 1RM partial squat in the literature for football players (52%) [8, 34]. A meta-analysis reported that FW RE is not superior to traditional RE for strength improvements [45], which corroborate our findings. Nevertheless, the difference in 1RM squat strength between the BFW and the FW group in our study is likely an effect of test specificity where the exercise performed by the BFW group was isotonic to the test; this is shown previously for the squat exercise [46]. Consequently, we urge for cautious interpretation when comparing 1RM gains between the BFW and FW group.

A previous meta-analysis comparing concentric and eccentric RE reported superior gains in maximal strength following eccentric RE [24]. However, their stratified analysis of exercise intensity revealed no differences between the two exercise modalities [24]. In fact, in studies comparing solely concentric low intensity (75% of 1RM) contractions with concentric and subsequent eccentric overload contractions (> 100% of 1RM), superior 1RM gains are reported from subsequent eccentric overload [47, 48]. While studies comparing solely concentric higher intensity (maximal 6- and 10RM and > 85% of 1RM) with subsequent eccentric overload reported similar gains in 1RM [49, 50]. This may suggest that as long as the concentric phase is performed with heavy loads (~ ≥ 85% of 1RM), no extra maximal strength gains can be derived from additional eccentric overload [24]. This indicate that high external loads (> 85% of 1RM) should be applied to easily recruit the higher threshold motor units [14], which is responsible for the highest force productions [13].

Strengths

To our knowledge, this is the first randomized controlled trial comparing FW RE to HL RE practices for maintaining [21] and improving [22, 23] sprint and jump height performance in football. Due to the comparison in our study, one can assess the applicability of FW RE in football. Such information is highly applicable for coaches in football clubs, which should use the best practice in relation to total exercise load to optimize performance of the players, at least in elite clubs.

Limitations

Some limitations need to be addressed. First, football involves multiple changes of direction at high velocities [51]. As changes of direction involves decelerations and subsequently accelerations in a different direction, the ability to utilize the elastic energy stored in tissues from deceleration during eccentric contractions into a subsequent concentric acceleration phase can be decisive in football [51]. Flywheel RE comprise of such decelerations with high force production, and FW RE is found to improve changes of directions [52]. We did not assess the ability to perform changes of direction our study. Future research investigating whether FW or HL BFW squat exercise results in superior performance in changes of direction tests is warranted.

Further, we did not match exercise intensity between the two intervention groups, which introduce the possibility of the external loads employed in the interventions influencing our results (i.e. the exercise intensity per se, not exercise modality). One study demonstrated that increasing FW inertia increases coupling time (transition from eccentric to concentric contraction during the movement) and reduces power output [53]. Thus, increasing FW inertia might have hindered maximal improvements in high velocity movements (sprint and jump height) for the players in the FW group. However, force production increased by increasing inertia [53] and the intended velocity per se (not actual movement velocity) is responsible for improving high velocity movements following RE [12]. As increasing force production with increasing inertia can be considered higher load RE than not increasing inertia, we increased inertia following mean > 4 watts·kg^{-1} in one set to label both intervention groups' exercise intensity "HL RE" and make exercise intensity between groups more comparable. Thus, we tried to keep similar progression in exercise load in both intervention groups, where reaching a certain limit (FW: > 4 watts·kg^{-1}, BFW: ≥ 5 repetitions) resulted in an increased load in the next set. This also ensured individualized progression, as highlighted as an important factor for optimizing improvements in sprint performance from FW RE [53].

Furthermore, by performing 4 × 4 repetitions and increasing load when reaching five repetitions in the BFW, without any mid-test 1RM to adjust relative load, there could have been a possibility of some players in the

BFW group exercising at < 85% of their actual 1RM as their actual 1RM increases during the intervention. However, this protocol is proved highly effective in improving maximal strength [21, 22, 34] and moreover, the increase from week to week was high in this group (Fig. 2), ultimately leading to a 46% increase in 1RM, which is towards the highest reported increases in 1RM in football players [8].

Hamstring muscle strength is associated with sprint performance [54–56], and antagonist co-contraction may have contributed to the increase in force production by an exercise-induced increase in reciprocal inhibition [57]. As both intervention groups performed the Nordic Hamstring exercise, the control group should also have performed this exercise allowing us to solely compare the effects of FW and BFW squats. However, the potential effects of Nordic Hamstring on sprint and jump height performance in our two intervention groups should influence our results in similar proportional order. Nevertheless, it seems that antagonist co-contraction plays a greater role in joint protection in RE, suggesting that they may play a minor role in the actual movement velocity [57]. Moreover, the effect on sprint performance following Nordic hamstring exercise is usually small [58, 59] or non-existing [60].

Finally, this study included recreationally active football players. Elite football players are reported to sprint faster than lower level players [1] and have a larger total exercise load resulting in limited recovery time between exercise sessions [20]. Whether differences in sprints, jump height and maximal strength gains from FW and BFW squats would be present in elite football players are currently unknown. However, as the players in our study experienced similar gains from BFW squats on sprint, jump height and 1RM partial squat as previously reported in elite football players [8, 22, 34], one may consider our study's findings generalizable to elite football players, at least until proven otherwise by future research.

Conclusion

Squats carried out with FWs or HL BFWs where both are performed with MIVCs and combined with football sessions, were equally effective in improving sprint time and jump height in football players. The BFW group experienced a more than two-fold larger increase in maximal partial squat strength than the FW group. This presents FW RE as an alternative to HL free weight RE for improving high velocity movements in football players.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s13102-020-00210-y.

Additional file 1. Supplementary file: zip-file containing the dataset analyzed for this study.

Abbreviations

RE: Resistance exercise; FW: Flywheel; HL: High load; BFW: Barbell free weight; SD: Standard deviation; 1RM: One repetition maximum; MIVC: Maximal intended velocity contraction

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Authors' contributions

LPRN, SAP, EHS, SP conceived and designed the study. EHS and LPRN generated random allocation sequence. LPRN enrolled participants and assigned participants to interventions. LPRN carried out data collection. EHS performed the statistical analyses. SAP, EHS, SP, AC, BW, MBR participated in data interpretation and analysis. EHS was in charge of the writing process. LPRN, SAP, EHS, SP, AC, BW, MBR participated in reviewing/editing the manuscript and all authors approved the final version of the manuscript.

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Availability of data and materials

All data generated or analysed during this study are included in this published article and its supplementary information files.

Ethics approval and consent to participate

This study was carried out in accordance to the Declaration of Helsinki; prior to pre-tests, all the players were informed of the purpose of the study and its associated risks and benefits, before providing oral and written informed consent. The Norwegian Data Protection Service approved the study and the storage of personal data (Approval reference number: 374030), without further Regional Ethical approval per applicable institutional and national guidelines for sport and exercise science [29, 30].

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Maximal Strength, Sprint, and Jump Performance in High-Level Female Football Players Are Maintained With a Customized Training Program During the COVID-19 Lockdown

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Introduction: The COVID-19 outbreak with partial lockdown has inevitably led to an alteration in training routines for football players worldwide. Thus, coaches had to face with the novel challenge of minimizing the potential decline in fitness during this period of training disruption.

Methods: In this observational pre- to posttest study involving Norwegian female football players (18.8 ± 1.9 years, height 1.68 ± 0.4 m, mass 61.3 ± 3.7 kg), we investigated the effects of a prescribed home-based and group-based intervention, implemented during the COVID-19 lockdown, on maximal muscular force production and high velocity variables. Specifically, maximal partial squat strength one repetition maximum (1RM), counter movement jump (CMJ) and 15 m sprint time were assessed 1 week prior to the lockdown and 12 weeks after the onset of lockdown. We also collected training content and volume from the prescribed training program and self-reported perceived training quality and motivation toward training.

Results: We observed no change in 1RM [pretest: 104 ± 12 kg, posttest: 101 ± 11 kg ($P = 0.28$)], CMJ height [pretest: 28.1 ± 2.3 cm, posttest: 26.8 ± 1.9 ($P = 0.09$)], and 15 m sprint time [pretest: 2.60 ± 0.08 s, posttest: 2.61 ± 0.07 s ($P = 0.52$)].

Conclusion: Our findings suggest that a prescribed home-based and group-based intervention with increased training time devoted to strength, jump, and sprint ability, and regulated to obtain a sufficient infection control level is feasible and effective to preserve strength, jumping, and sprinting abilities of high-level female football players during a ∼ 3-month period of a pandemic-induced lockdown.

Keywords: resistance training, sprint, soccer, counter movement jump, squat, COVID-19

INTRODUCTION

In 2019 and 2020, the COVID-19 outbreak resulted in country lockdowns where both the general population and athletes were exposed to unexpected behavioral restrictions (e.g., social distancing, closure and/or limitation of non-essential activities such as gyms and training grounds, and ultimately, self-isolation). Strict quarantine rules were introduced following national/international travel, after direct exposure to the virus or if showing COVID-19 symptoms. Consequently, athletes were enforced to cancel and/or postpone their competitions and to abruptly adjust their training routines (Sarto et al., 2020). In Norway, these regulations were imposed for all sports and were introduced during football teams' pre-season preparations. This led to a rapid shift in training plans and training practice with for example, some teams prescribing home-based training for their players (Sarto et al., 2020).

Football fitness includes both aerobic and anaerobic-capacity, and explosive muscle actions (Bangsbo et al., 2006). For example, dynamic muscle strength such as partial squat one repetition maximum (1RM) is suggested to reflect functional strength of football players (Wisløff et al., 1998), which is associated with muscular power (Stølen et al., 2005) and the ability to perform football specific actions (Wing et al., 2020). Mimicking the movement patterns in football during training was challenged during the lockdown period, which may have led to declines in football-specific physical fitness (Mohr et al., 2020).

One of the main intentions of the pre-season period in football is to optimize physical performance including jumping and sprinting ability, and maximal strength (Rønnestad et al., 2011). However, how these abilities are affected when the pre-season is unexpectedly interrupted, is mostly unknown. Several researchers have suggested negative effects of self-isolation following the COVID-19 lockdown (Mohr et al., 2020; Sarto et al., 2020), suggesting that it may result in lower training volume and quality, and in turn, decreased physical fitness (Girardi et al., 2020; Sarto et al., 2020). Indeed, a number of studies have reported reduced physical activity (Xiang et al., 2020; Zheng et al., 2020) and training hours during the COVID-19 lockdown (Mon-López et al., 2020; Zinner et al., 2020), and there are already findings of decreased cycling performance in cyclists (Muriel et al., 2020) and reduced hamstring strength in football players (Moreno-Pérez et al., 2020). However, some have presented the potential of maintaining physical fitness in multidisciplinary sports such as football, by performing circuit-based training (Latella and Haff, 2020). This was recently shown in a male football team, where jump height was preserved following 15 weeks of isolated training (Cohen et al., 2020).

Longer periods without strength training (12 weeks) may lead to reduced strength of 7–12% in strength trained individuals (Mujika and Padilla, 2000). Importantly, small quantities of training can attenuate the strength loss following complete training cessation in high levels athletes (García-Pallarés et al., 2010). Our planned data collection involving female football players was abruptly interrupted by the pandemic. Thus, we had the opportunity to investigate whether a change in prescribed training designed to limit COVID-19 infection during lockdown (home-based, group based, and without normal football play), could preserve 1RM partial squat strength, counter movement jump (CMJ) and 15 m sprint time. To the authors' knowledge, the effect of COVID-19 related training adjustments on strength and strength derivatives is only available in male football players (Cohen et al., 2020; Moreno-Pérez et al., 2020). Thus, the aim of our study was to assess the effects of a prescribed unsupervised 12-week home- and group-based training program without gym facilities on 1RM partial squat strength, CMJ and 15 m sprint time in female high-level football players during a period without full contact football training.

MATERIALS AND METHODS

Design, Subjects, Procedure, and Questionnaires

Our study is a longitudinal 12-week observational study with a pretest posttest design. Two female football teams playing at level three in Norway were originally invited to another study, whose main aim was to investigate the association between high-force/power tests and physical performance derived from tracking data during football match play. Since the COVID-19 lockdown was imposed by national authorities 1 week following pretest start, and 1 day prior to pretest the second team ($n = 13$) (**Figure 1**), the team that completed the lab tests ($n = 13$) involved in that study were invited to participate in a new data collection (posttest) 12 weeks after the first visit to the laboratory. Four players had left Tromsø for personal reasons during the lockdown period, thus nine players attended the follow-up measurements and were eligible for this study (**Table 1**). The lockdown was introduced 4 weeks prior to the planned start of the competitive season for the team. Data for eight players is reported for the force data acquisition in the CMJ test and eight players for 1RM, due to incomplete force data recording in the CMJ for one player at pretest and a hand injury at posttest for another player. Eight players are included in the dexa-scan data. All the other variables are reported for pre- and posttest for all nine players. The training plan information was retrieved from the team's coaches (**Table 2**).

According to the Helsinki declaration, all participants were informed of the potential benefits, risks, and procedures of the study, both orally and in writing, before signing an informed consent. The original study and the data storage protocol was approved by the Norwegian Center for Research Data (NSD) (approval reference number: 989024), and approved our changed aim and a new data collection period in June (correction reference number: 768380), without any further ethical approval per institutional and national guidelines for research on sport and exercise science.

At pretest, the players answered one custom-made question about their experience with strength training in the squat exercise with answering option 1, No experience; 2, Some experience (<1 year); and 3, A lot of experience (>1 year). Two months after posttest in June 2020, the players received an individual custom-made questionnaire about their pre-season training habits before

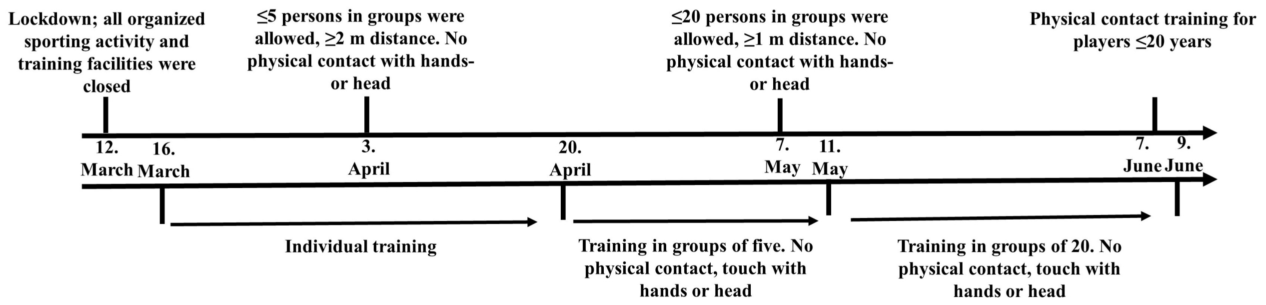

FIGURE 1 | Timeline of COVID-19 regulations affecting the team in the current study. The chart displays both the governmental and football associations' regulations (upper side of the line) and the teams' prescribed training to these regulations (lower side of the line). Pretest was carried out prior to the first date in the scheme, while posttest was performed immediately after the last date.

TABLE 1 | Baseline participant characteristics (mean ± SD).

Age (year)	18.8 ± 1.9
Body mass (kg)	61.3 ± 3.7
Height (m)	1.68 ± 0.4
Lean mass (kg)	44.5 ± 2.0
Bone mass (kg)	2.66 ± 2.0
Body fat (%)	24.88 ± 0.04
Fat mass (kg)	14.9 ± 3.5
Leg lean mass (kg)	15.4 ± 8.6

Body composition is measured by a dual-energy X-ray absorptiometry machine (dexa-scan) (Lunar Prodigy; GE Medical Systems, Buckinghamshire, United Kingdom).

TABLE 2 | Changes in prescribed training from pre- to posttest, before and during lockdown.

	During normal pre-season training before lockdown	During lockdown	%-change
Total training (min)	291 ± 77	233 ± 47	−20
Football training (min)	207 ± 55	95 ± 106	−54
Strength training (min)	28 ± 27	40 ± 39	43
Speed and jump training (min)	6 ± 13	26 ± 19	333
Endurance training, running (min)	0 ± 0	45 ± 39	NA
Individual training (sessions)	0.3 ± 0.5	2.0 ± 2.0	567
Group/team training (sessions)	3.6 ± 0.7	1.8 ± 1.7	−50

Weekly training prescribed by the coaches to their players during the spring 2020. The data is presented as average minutes ± SD.

and during the lockdown. This consisted of six questions where the first reflected their adherence to the training prescribed by the coaches during the lockdown, in a bipolar five-unit Likert-scale. The second and third question were about their perceived quality of training and motivation to training, respectively, answered on a bipolar three-unit Likert scale. These three questions were first addressed for the pre-season period prior to the lockdown, and subsequently for the period after the lockdown. The questionnaire was designed by two researchers (SP and SAP), and later discussed by additional two researchers (BW and TH) where the final version was developed with consensus from all four researchers.

Prior to pretest, all the participants underwent 3–4 supervised familiarization sessions to the partial squat exercise over 2 weeks, in order to perform the movement safely and technically sound (Ploutz-Snyder and Giamis, 2001). All tests and familiarization sessions started with the same standardized warm-up routine consisting of 5 min of self-selected low intensity cycling on an ergometer bike (Pro/Trainer, Wattbike Ltd., Nottingham, United Kingdom) and followed by 5 min low intensity running of self-selected speed in the gym. The participants were recommended to not perform strenuous physical exercise 24 h prior to testing. Pretests of physical fitness (e.g., 1RM, CMJ, and 15 m sprint) were conducted in the laboratory between 17:00 and 19:00 on two separate occasions, separated by 3 days. During the first day, the sprint tests were carried out first followed by the CMJ test; thereafter half of the players underwent the dexa-scan. On the second day, the players underwent a 1RM test, followed by a dexa-scan for the second half of the players.

Strength

The participants underwent a 1RM test in the partial back squat exercise for the assessment of maximal dynamic strength. An Olympic barbell (T-100G; Eleiko, Halmstad, Sweden) was used for both familiarization and the main experimental testing. During the 1RM trials, the participants were instructed to lift the bar from the rack, step one step back, go slow into the descending phase of the movement, followed by a maximal intended velocity during the concentric phase. The participants initiated the concentric phase as response to an orally "go" by the researcher measuring the 90° knee angle at the knee joint with a goniometer (Pedersen et al., 2019). The same researcher measured knee angle for all the participants during both pre- and posttest. The participants warmed up with 10 repetitions by lifting the bar (20 kg), followed by 10 repetitions of the participants' perceived ∼50% 1RM. The starting 1RM attempt consisted of one repetition at a high load, which the participants knew they could manage. Each following attempt was completed with 5–10 kg additional load until failure. All players had a minimum of 3 min rest between each lift. The highest load lifted by the participants was defined as their 1RM.

Sprint

Prior to the sprint test, in addition to the general standardized warm up, the participants performed three 15 m strides at their subjective effort of 85–90% of maximal acceleration speed. Thereafter, the participants performed three, 15 m sprints with 3 min rest between each attempt. The sprint times were measured by single-beam electronic photocells (ATU-X, IC control AB, Stockholm, Sweden) mounted to the floor and walls. The starting photocell was placed 20 cm above the ground, while the 5, 10, and 15 m photocells were placed 100 cm above the ground. Self-initiated, the players started the sprint in a static position placing their front foot 30 cm behind the starting line. The fastest 5, 10, and 15 m split times were included in the analyses.

Counter Movement Jump

Standing on the force platform (Hur-Labs, ALU4, Finland), the participants were instructed to perform a CMJ with the aim to jump as high as possible, with the hands fixed on the hips during the entire movement. Force data were recorded with bespoke software (Force platform software suite, HURlabs oy, Kokkola, Finland). The software calculates jump height as the center of mass displacement calculated from the force developed and measured body mass. Each player performed two trials with a minimum 3 min rest between the two trials. The highest jump was taken for analysis.

Statistical Analyses

The Shapiro–Wilk test and visual inspection of Q–Q plots were used to assess normality distribution of data. For 1RM, CMJ, and 15 m sprint times we used Student paired sample *t*-tests to determine the change from pre- to posttest. For training and questionnaire data, non-parametric tests were used for analyses as these variables were considered non-normally distributed. For the questionnaire data (e.g., training adherence, quality, and motivation), we used a non-parametric signed rank tests to assess the direction of the data from pre-post lockdown (Roberson et al., 1995). All data are presented as mean ± standard deviation (SD), or 95% confidence intervals (CI). Alpha level was set to 0.05. The Statistical Package for the Social Sciences (SPSS, Version 26, IBM, Armonk, NY, United States) was used for the statistical analyses.

RESULTS

Six of the players reported to have some experience with strength training using the squat exercise, while the three remaining players reported to have a lot of experience.

The pre- and posttest results are presented in **Table 3**, with the individual percentage changes illustrated in **Figure 2**. No significant changes were observed for absolute- and relative 1RM partial squat strength ($P > 0.05$), CMJ jump height ($P > 0.05$), force production variables in the CMJ test (all $P > 0.05$), or in 15 m sprint times ($P > 0.05$, in all cases) from pre- to posttest.

Change in perceived adherence to the prescribed training and perceived level of motivation toward training were both non-significant ($P > 0.05$), while perceived quality of training was significantly reduced from pre- to posttest ($P < 0.05$) (**Figure 3**).

DISCUSSION

Our study describes the effects on partial squat 1RM, CMJ, and sprint performance in female football players during a period of a global pandemic, which resulted in comprehensive adjustments of players' training routines. Our main findings were that maximal strength, sprint time and jump performance did not decrease during lockdown.

Researchers have speculated that COVID-19 induced restrictions will lead to training cessation and consequently physiological detraining during (Girardi et al., 2020), where football players first trained in solitude, followed by a second

TABLE 3 | Changes in selected parameters from pre- to posttest.

	Pre (mean ± SD)	Post (mean ± SD)	Change (mean and 95% CI)	*P*-value
Partial squat 1RM				
1RM (kg)	104 ± 12	101 ± 11	3 (3; 8)	0.28
1RM (kg·m_b^{-1})	1.69 ± 0.24	1.65 ± 0.23	0.03 (− 0.05; 0.12)	0.39
15 m sprint test				
5 m (s)	1.03 ± 0.04	1.04 ± 0.05	0.01 (− 0.05; 0.03)	0.52
10 m (s)	1.86 ± 0.05	1.88 ± 0.05	0.01 (− 0.04; 0.01)	0.28
15 m (s)	2.60 ± 0.08	2.61 ± 0.07	0.01 (− 0.04; 0.03)	0.68
CMJ				
Jump height (cm)	28.1 ± 2.3	26.8 ± 1.9	1.4 (− 0.26; 2.98)	0.09
Takeoff velocity (m s^{-1})	2.34 ± 0.10	2.29 ± 0.08	0.05 (− 0.03; 0.13)	0.17
Maximum force (N)	1274 ± 70	1265 ± 73	9 (− 58; 77)	0.75
Maximum power (W)	2665 ± 167	2605 ± 109	60 (− 96; 216)	0.40
Flight time (ms)	490 ± 26	485 ± 18	5.6 (− 15; 26)	0.57
Average power (W)	628 ± 89	591 ± 76	36 (− 8; 81)	0.10
Average force (N)	763 ± 37	747 ± 37	16 (− 8; 40)	0.15

CMJ, counter movement jump; 1RM, one repetition maximum. P, the P-value from the paired sample t-test from pre- to posttest.

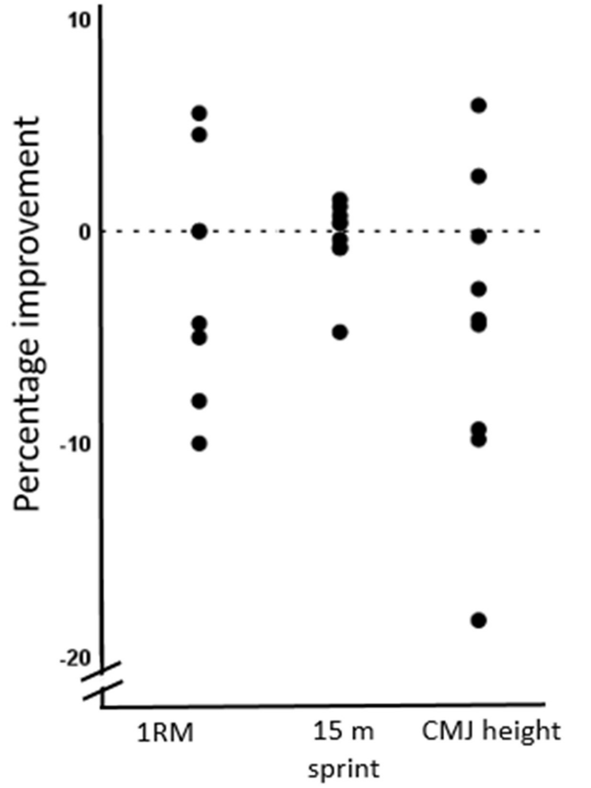

FIGURE 2 | Percentage changes for each individual participant from pre- to posttest for absolute one repetition maximum in the partial squat exercise (1RM) (kg), 15 m sprint time (s) and counter movement jump (CMJ) height (cm).

stage in which training was performed in small groups with contact restrictions (Mohr et al., 2020). The team in our study had a total weekly training volume of ∼ 5 h prior and ∼ 4 h during the lockdown, which was a decreased total training time (∼1 h). This is less than the ∼ 3.5 h reduced training time recently reported for female football players in the three highest leagues in Spain during the lockdown (Mon-López et al., 2020). The participants in our study tended to perform more strength training during the lockdown, potentially compensating for the loss of sports specific training during this period. This increase in strength training time did not increase strength, jump, or sprint performance, but rather maintained it. Importantly, our results reflect the prescribed training from the coaches, and not the reported training performed by the players, as in the study by Mon-López et al. (2020). However, their initial training volume was probably much higher than in the current study, as their self-reported weekly training pre-lockdown was 12 h. The training volume in our study is much lower than for elite players. Self-reported training data from the first and second placing team in the highest division in Norway last season, showed that the players trained 9.2 ± 2.5 weekly hours during the preseason (unpublished results).

We did not expect that reduced football training *per se* would lead to a marked strength loss, as football training do not seem to influence maximal strength (Rønnestad et al., 2008). We rather expected that no access to the team's- and commercial gyms might have a negative influence on maximal strength during the COVID-19 period. Recently, one study found that a group of semi-professional male football players reduced hamstring muscle strength following 25 days of home confinement due to the COVID-19 lockdown (Moreno-Pérez et al., 2020). However, these findings are not directly comparable as the muscles, exercise modality and muscular contraction type (Nordic hamstring, an eccentric contraction exercise) were different for the strength test in the study by Moreno-Pérez et al. (2020) than in our study. Eccentric strength is more susceptible to decline compared to other neuromuscular factors (Mujika and Padilla, 2001). This may explain the discrepancy between our study and the study by Moreno-Pérez et al. (2020), as the partial squats in our study emphasize concentric strength.

Highly strength trained athletes are more susceptible to decrements in strength following training restriction compared to less trained (Rønnestad et al., 2011). The prescribed training by the team in our study prior to the lockdown consisted of little time devoted to strength training (**Table 2**). Hence, pretest 1RM was likely not influenced by systematic maximal strength training in the players in our study. For example, our study's players' 1RM was similar to the baseline 1RM partial squat strength in another study of female football players, which increased their 1RM squat strength by 30% following 5 weeks of strength training (Pedersen et al., 2019). However, although the players in our study reported to have some experience with the squat exercise, it may be that their exercise modalities were ineffective or non-specific, thus their maximal partial squat strength was relatively low compared to the levels expected following systematic strength training (Pedersen et al., 2019).

The sprint time for 15 m accompanied by split times at 5 and 10 m did not change during the lockdown. A study by Sporis et al. (2011) showed that starters in official matches improved sprint performance more than non-starters over a season. Specific small-sided games are typically used as training drills during normal football training. Small-sided games are shown to both provoke high maximal acceleration distance during play (Ade et al., 2014) and improve sprint performance (Hammami et al., 2018). However, sprinting is an uncomplicated movement pattern to carry out outside the football field where especially short sprints can be trained almost anywhere without the use of equipment, and consequently lead to improvements in acceleration (Spinks et al., 2007), or sprint performance maintenance, as found in our study, being in line with earlier findings (Mujika et al., 2009). The sprint training effect is usually not superior when a supervising coach is included compared with individual unsupervised sprint training (Haugen et al., 2015). Thus, sprint-training effect solely relies on the players themselves, where the players in our study performed sufficient amounts to preserve sprint performance. The prescribed volume of sprint and jump training time showed a tendency to increase during the lockdown (**Table 2**), and may have compensated for the reduced specific football training.

The CMJ height was preserved during the lockdown. This is in line with recent findings in male football players

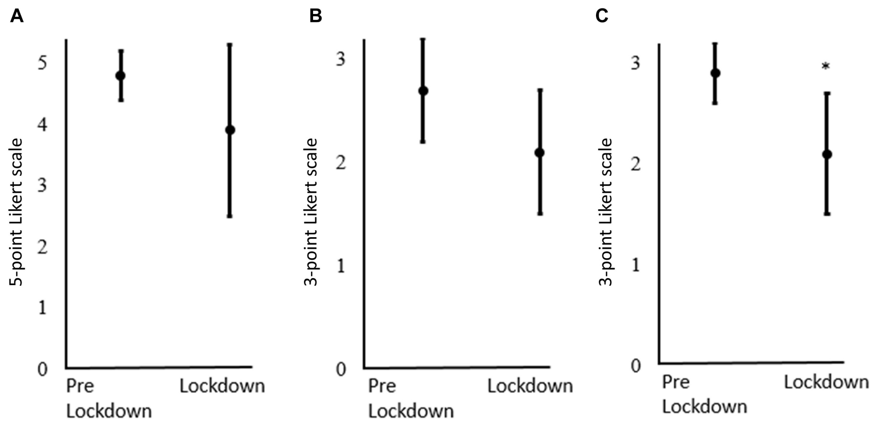

FIGURE 3 | (A) Perceived adherence to proportion of the prescribed training plan [*y*-axis, 1. to a little degree (0–20%), 2. to some degree (21–40%), 3. approximately half (41–60%), 4. to a large degree (61–80%), 5. almost all (81–100%)]. **(B)** Perceived degree of motivation for training (*y*-axis, 1. highly motivated, 2. average motivated, 3. low motivated). **(C)** Perceived level of quality of the training conducted (*y*-axis, 1. high quality, 2. average quality, 3. low quality). The figure displays the mean ± SD. *Indicates a significant difference ($P < 0.05$) from pre lockdown to lockdown, derived from the Signed rank test.

(Cohen et al., 2020). Jump performances as during heading situations are observed in large sided football games (Owen et al., 2014). In order to follow the regulations by the authorities, both large sided and small-sided games were not performed by the team in the current study during the lockdown. With total training cessation, jump height decrements are reported following 4 weeks in adult males (Izquierdo et al., 2007), but not following 3 weeks in adolescent males (Gavanda et al., 2020). Maximal power is likely better preserved than maximal force (Bosquet et al., 2013). Importantly, the reduction is shown to be more profound as the training cessation duration increases, where maximal force declines are reported following 3 weeks of training cessation (Bosquet et al., 2013).

Others have found reduced jump height after an off-season training program (Koundourakis et al., 2014). The same is shown for sprint performance (Clemente et al., 2021). However, if the players are given an exercise plan during the off-season with gym sessions implemented, sprint and jump maintenance is possible (Requena et al., 2017). In our study, the players had not access to gyms, and were thus no able to implement proper maximal strength training in line with previous recommendations (Rønnestad et al., 2008; Helgerud et al., 2011). However, they still managed to implement a feasible training regimen sufficient to preserve strength levels. In total, the preserved strength, jump, and sprint performance during the COVID-19 lockdown in the team in our study is likely an effect of adhering to a well-designed physical training program, which according to our questionnaire was well implemented by the participants. For players of this level, strength training in the gym or full contact football trainings are not necessary to maintain maximal strength, running speed or jump ability.

Limitations

The main limitation in the current study is the low sample size, which increases the possibility of a statistical type 2 error, and such a consequence cannot be conclusively ruled out. However, to our knowledge this is the first study to report pre- and posttest prior and following the COVID-19 lockdown in female football players. Due to the uncontrolled design of our study, it should be considered descriptive and thus report changes in acceleration and jump height over the COVID-19 training period. Unfortunately, this design does not allow for causality inference (i.e., why we observed no change in performance). This information is highly relevant for football coaches. Second, although the training was described by the coaches, we do not know whether the players adhered to the training regimen, which we measured in retrospect with a subjective rating on the Likert scale.

CONCLUSION

Maximal partial squat strength, CMJ, and sprint performance were preserved in female football players during a 12-week period of absence from normal football training and gym facilities during the COVID-19-induced lockdown. Thus, all the variables reflecting maximal and rapid muscular force production remained unchanged, likely due to adherence to a well-designed home-based and group-based training program by the team's coaches.

Future Steps and Recommendations

Furthermore, as football is a complex sport in its requirements for different physical aspects, coaches should consider breaks like those that we have experienced due to COVID-19 as opportunities, and prioritize endurance, speed and power training in lieu of specific football training.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

SP: in charge of the writing process, conceptualization and design, and data collection. SAP and DJ: conceptualization and design, and critical manuscript revision. AW and ES: contribution to data collection, statistical analyses, and manuscript revision. BW: conceptualization and design, contribution to statistical analyses, and critical manuscript revision. MR and AC: contribution to critical manuscript revision. All authors contributed to final approval of the version to be published.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Questionnaire from paper IV

Spørsmål angående trening før og etter Coronapandemien inntraff

Dette spørreskjemaet angår to perioder:
1. De første 10 ukene i vinter/vår før coronapandemien inntraff Norge.
2. Perioden etter 12. mars og frem til sommerferien.
Kryss av i den ruten du mener best beskriver din trening. Svar med ett kryss per spørsmål.
Send ferdig utfylt skjema til sigurd.pedersen@uit.no

Din ID (bruk kun initialer):

☐

Spørsmål 1-3 omhandler perioden etter nyttår, før coronaen inntraff.

Spørsmål 1.
I hvilken grad fulgte du den oppsatte treningen under de **10 ukene av forsesongen før coronapandemien inntraff**?

1. I veldig liten grad (0-20%) ☐
2. Til en viss grad (21-40%) ☐
3. Ca. Halvparten (41-60%) ☐
4. I ganske høy grad (61-80%) ☐
5. Nesten til punkt og prikke (81-100%) ☐

Spørsmål 2.

Hvor motivert var du for trening under de **10 ukene av forsesongen før coronapandemien inntraff**?

1. Veldig motivert ☐
2. Middels motivert ☐
3. Lite motivert ☐

Spørsmål 3.

Hvordan vil du vurdere treningskvaliteten under de **10 ukene av forsesongen før coronapandemien inntraff**?

1. Høy kvalitet ☐
2. Middels kvalitet ☐
3. Lav kvalitet ☐

Spørsmål 4-6 omhandler perioden etter coronaen inntraff, og frem til sommerferien.

Spørsmål 4.
I hvilken grad fulgte du den oppsatte treningen under de **12 ukene etter at coronapandemien inntraff** og frem til sommerferien?

1. I veldig liten grad (0-20%) ☐
2. Til en viss grad (21-40%) ☐
3. Ca. Halvparten (41-60%) ☐
4. I ganske høy grad (61-80%) ☐
5. Nesten til punkt og prikke (81-100%) ☐

Spørsmål 5.

Hvor motivert var du for trening under de **12 ukene etter at coronapandemien inntraff** og frem til sommerferien?

1. Veldig motivert ☐
2. Middels motivert ☐
3. Lite motivert ☐

Spørsmål 6.

Hvordan vil du vurdere treningskvaliteten under de **12 ukene etter at coronapandemien inntraff** og frem til sommerferien?

1. Høy kvalitet ☐
2. Middels kvalitet ☐
3. Lav kvalitet ☐