Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Medicine and Health Sciences

Vetle Veierød

Comparative Effects of Half-back Squat and Nordic Hamstring on Sprint Performance in Youth Male Soccer Players

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Supervisor: Ulrik Wisløff

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Abstract

Background: Sprint performance is related to game-decisive moments in soccer, and the number of sprints is related to success. Maximal strength training (MST) is considered an effective method to improve sprint performance. Biomechanics and EMG analysis show that the quadriceps and gluteals are crucial in the acceleration phase, whereas eccentric hamstring strength is crucial at higher speeds. The half-back squat (HBS) exercise mainly targets the quadriceps and gluteals, and the Nordic hamstring (NH) targets the hamstrings eccentrically.

Aim: We aimed to study and compare the effects of HBS and NH on sprint performance at different sprint distances in youth male soccer players after 9 weeks of MST.

Method: Twenty-three youth male soccer players (15.2 ± 1.3 years, 62.9 ± 9.8 kg, 176.7 ± 8.3 cm) were randomly allocated to either a Half-back squat (HBS) group (n = 12) or an NH group (n = 11). An age-matched soccer team was used as a control group (n = 12). HBS and NH groups performed 9 weeks of two weekly maximal strength training (MST) sessions in their allocated exercise. All players tested 40 m straight-line sprint (split times: 5, 10, 20, 30, and 40 m), change of direction (COD) sprint, and countermovement jump test (CMJ). The HBS group tested HBS 1RM, and NH group tested NH peak force (PF). **COVID-19 outbreak:** Norway went into lockdown March 12th which forced us to cancel the post-tests. Baseline tests were used to study and compare the relationship between HBS 1RM ($kg \cdot bw^{-0.67}$) and sprint performance, and NH PF ($N \cdot bw^{-0.67}$) and sprint performance.

Results: HBS 1RM ($kg \cdot bw^{-0.67}$) correlated better with greater sprint distances compared to shorter (i.e. 0-5 m: r = -0.69, p = 0.60, 10-30 m: r = -0.93 < 0.001.) The same was evident for NH PF ($N \cdot bw^{-0.67}$) (i.e. 0-5 m: r = -0.49, p = 0.176, 20-40 m: r = -0.86, p = 0.003). HBS 1RM ($kg \cdot bw^{-0.67}$) was higher correlated with sprint times on all sprint distances and COD compared to NH PF ($N \cdot bw^{-0.67}$).

Conclusion: Correlations indicate that HBS and NH may be more effective in improving sprint times at greater sprint distances compared to shorter (i.e. after 10 m), and that HBS may be superior to improve overall performance in both straight-line and COD sprinting.

***Keywords**:* Half-back squat, Nordic hamstring, soccer, sprint, maximal strength, peak force

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Abbreviations

1RM: One-repetition maximum

bw: Bodyweight

COD: Change of direction

CG: Control group

CMJ: Countermovement jump

EMG: Electromyography

HBS: Half-back squat

H:Q: hamstring-to-quadriceps ratio

MST: Maximal strength training

N: Newtons

NH: Nordic Hamstring

PF: Peak force

RS: Repeated sprint

RFD: Rate of force development

SSC: Stretch-shortening cycle

INTRODUCTION

Although most activities in soccer are of low-intensity, the most game-decisive actions are those of explosive- and high-intensity nature such as accelerations, decelerations, sprints, jumps, and change of directions (COD) (Barnes et al., 2014; Bloomfield et al., 2008; Bradley et al., 2009; Burgess et al., 2006; Di Salvo et al., 2007; Faude et al., 2012; Rampini et al., 2007; Vigne et al., 2010). Sprinting in soccer can be categorized into straight-line sprinting, COD sprinting, and repeated sprint (RS) ability. Further, straight-line sprinting can be divided into acceleration, maximal running velocity, and deceleration (Mero et al., 1992). In match analysis, the classification of sprinting is differing, but most studies define sprinting as running speed >25.2 km/h over a 0.5 second time interval (i.e. Carling et al. 2010; Di Salvo et al. 2007; Di Salvo et al., 2009). Acceleration and deceleration profiles are difficult to contextualize as there is a large distinction in the methods used. However, Dalen et al. (2016) have attempted to more clearly establish a method that can be replicated. They defined accelerations and decelerations as follows: acceleration/deceleration has to reach the minimum limit of 1 $m \cdot s^{-2}$ for the event to start, as well as reaching a speed of 2 $m \cdot s^{-2}$ and last for at least half a second to be counted.

Analysis of every goal from the second half of the German Bundesliga 2007/2008 season showed that 83% of the goals came from explosive actions from the assisting and/or the scoring player. Of these, 64% was from straight sprinting, 9% from COD sprints, 17% from jumps, and 10 % from rotation (Faude et al., 2012). Further, up to 2005, research established that sprints in elite soccer were performed approximately every 90 s (reviewed in Stølen et al., 2005), while others reported sprint frequencies in the range of 17-81 per game for each player (Burgess et al., 2006; Di Salvo et al., 2007; Vigne et al., 2010). However, from the 2006/07 to 2012/13 season in the English Premier League, the number of sprints and total sprint distance have increased by 85% and 35%, respectively (Barnes et al., 2014). Moreover, match analysis shows that more than 90% of all sprints performed in soccer are shorter than 20 m, and that mean sprint duration is between 2 and 4 seconds (Burgess et al., 2006; Vigne et al., 2010). This may indicate that acceleration capabilities are of higher importance than top speed in modern soccer. However, it is important to note that the importance of peak velocity increases when sprints are started from non-stationary or jogging condition (Haugen, 2014). Soccer players rarely start sprinting from a stationary condition (Balsom, 1994; Haugen, 2014). From a stationary start, the 20-m sprint times of elite soccer players in a study by Helgerud et al. (2011) ranged from 2.90 to 3.29

seconds, and it is shown that 80 to 90% of maximal sprint velocity is achieved already after 2-3 s (Chelly & Denis, 2001; Graubner & Nixdorf, 2011). Thus, close to maximum velocity will be reached before 20 m if starting from a non-stationary condition. This speed will not be documented in studies that only test sprint, from a stationary position, at distances up to 20 m. In addition, the sprints that are longer than 20 m are probably decisive sprints as they often can be seen in counterattacks and in one-on-one sprinting duels between a striker and defending player after a through-pass. Therefore, although most sprints are shorter than 20 m, top speed capacity may be of equal importance as the capacity to undertake shorter sprints. Further, it is reported that each player performs around 600 accelerations and decelerations (regardless of intensity) in a game (Bloomfield et al., 2007). More recent studies have quantified the amount of high-intensity accelerations and decelerations. Dalen et al. (2016) reported 76 accelerations and 54 decelerations, whereas accelerations and decelerations contributed to 7-10% and 5-7% of the total player load for all positions. In addition, Varley & Aughey (2012) reported that maximal accelerations occur at a rate 8 times higher than maximal sprinting. Lastly, the amount and length of sprints may differ between specific playing positions and based on the team tactics, with wide defenders, wingers, and attackers having the highest sprinting demands (Di Salvo et al., 2007; Andrzejewski et al., 2015).

Regarding COD sprinting, Bloomfield et al., (2007) analyzed physical demands in the 2003/04 season in the FA Premier League Soccer. The analysis showed that a total of 727 COD actions was performed each game. Of these, 609 of was performed between 0-90°, 94 was performed between 90-180°, 6 between 180-270° and 2 between 270-360°, while 16 was categorized as swerve (changing direction abruptly). Furthermore, Faude et al., (2012) showed that 9% of the goals scored in the Bundesliga 2007/2008 season came after a COD during a sprint. Therefore, changing direction within sprinting also seem to be key in game decisive moments. Thus, being able to perform fast COD sprints are important in soccer.

Theoretically, improving your 5-m sprint by 0.09 s, 10-m sprint by 0.1 s, and 30-m sprint by 0.19 s, will theoretically mean an improvement in length corresponding to 0.38-, 0.53-, and 1.35 m, respectively. This can be the difference between winning or losing the ball and scoring or preventing a goal. This highlights the importance of acceleration and sprinting speed in soccer. Therefore, as accelerations and sprinting are performed frequently, related to game-decisive moments, and a small improvement in sprint speed can be the difference between winning or losing, soccer players should aim to improve their maximal acceleration and sprint speed.

However, improving single sprint performance would be of limited interest in soccer if it does not transfer to improved time on RSs as RS ability is a key factor in soccer and decisive for players' performance (Impellizzeri et al, 2008; Rampini et al. 2007). Although RS ability may be correlated with endurance components (Rampini et al., 2009), studies show that improved single sprint performance leads to less total time spent on RS tests. Both Pyne et al. (2018) and Ishøi et al. (2018) observed that improving your single sprint performance also leads to less total time on a RS test. Even the last sprint in the post-test was faster than the last sprint in the pre-test. Thus, improving your single sprint performance should be of high interests as it transfers to improved RS performance as well.

Methods to improve sprint performance

As soccer is dominated by power actions, maximal strength training (MST) is a key method to improve these abilities, as it may improve both maximal strength and rate of force development (RFD) (Bird et al., 2005; Helgerud et al., 2011). Maximal strength is the product of force and velocity, and Newtons 2nd law of motion states that for a given mass (the players bodyweight), acceleration is directly proportional to force magnitude. Thus, an increase in maximal strength, without a change in bodyweight, could improve acceleration and sprint performance. MST should be performed with high intensity loads (85-90% of one-repetition maximum (1RM)), a maximum of 5 repetitions, and 3-5 sets with 3 minutes rest between the sets (Bird et al., 2005; Cormie et al., 2010; Støren et al., 2008; Rønnestad et al., 2011; Heggelund et al., 2013). Importantly, the intentional velocity of the execution of each repetition is more important than the actual velocity for improving RFD (Behm & Sale, 1993). Thus, the velocity of the repetition can be slow as long as the intentional velocity is maximally executed. This is to ensure optimal neural adaptations and to stress all motor units to achieve maximal muscle activation (Behm, 1995).

Importantly, Wisløff et al. (2004) reported a strong correlation between maximal strength, sprint performance and vertical jump height, while Seitz et al. (2014) performed a meta-analysis on the topic and concluded that there is a strong significant correlation between maximal squat strength and sprint performance ($r = -0.77$, $p < 0.001$). In addition, Helgerud et al. (2011) demonstrated that soccer players improved 20-m sprint performance after 8 weeks of Half-back squat (HBS) MST. Therefore, MST that targets the musculature involved in sprinting could be a suitable method to improve sprint performance in soccer players. To know how to incorporate MST to improve sprint performance, it is crucial to have knowledge about the biomechanics of sprinting and in what phases of the sprint the different musculature is involved. In this way, we can also choose exercises to improve sprint performance and investigate the effect in different phases of the sprint, which should be of interest as one player may need to improve acceleration, while another needs to improve top speed.

Biomechanics of sprinting

To attain a full understanding of the biomechanics of sprinting, analysis of movement, force generation, and muscle action, is required. With electromyography (EMG) analysis of sprinting, the patterns of muscle activation can be determined, which is crucial for understanding how the muscles involved act to produce an effective sprint running action. Biomechanical examination of sprinting and EMG analysis of musculature used during sprinting demonstrates that the knee-extension musculature (quadriceps) and hip-extension musculature (hamstrings and gluteals) muscles are prime movers in sprinting (Guskiewicz et al., 1993; Howard et al. 2018). However, the level of activation for the musculature involved during sprinting is different in each phase of the sprint (Ditroilo et al., 2001; Nummela et al., 1994; Paul &Wood, 2002). Importantly, the EMG analysis must be viewed in relation to the existing kinematics and kinetic analysis of sprinting and be analyzed in each phase of the running gait cycle. Together, they can provide fitness coaches and players with advanced knowledge regarding optimal strength training exercises for different sprinting abilities.

The key phases of the running gait cycle can be divided into four phases: The early stance phase (braking phase), the late stance phase (propulsion phase), the early and middle swing phase (recovery phase), and the late swing phase (pre-activation phase) (Novacheck, 1998; Nummela et al., 1994; Pinniger et al. 2000; Yu et al., 2008). The early stance phase begins when the foot makes initial contact and ends at the middle stance phase (estimated at 0-15% of the cycle). The late stance phase begins at the middle stance phase and ends at the toe off (estimated 15-30% of the cycle). The early and middle swing phase begins at toe off and ends approximately two-thirds of the way through the swing phase (estimated at 30-77% of the cycle). Lastly, the late swing phase begins at two-thirds of the swing and ends at the initial contact (estimated 77-100% of the cycle) (figure 1, taken from Howard, (2018)).

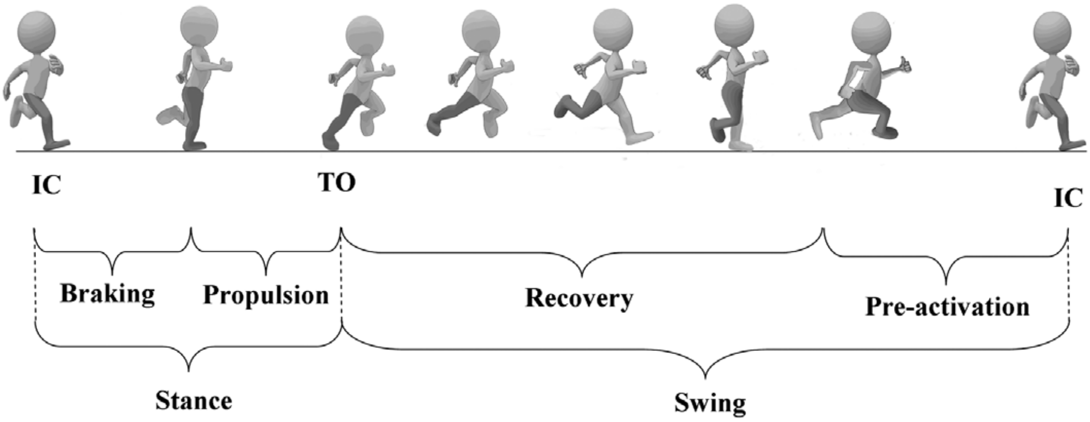


Figure 1 The Phases of sprinting. IC, initial contact; TO, toe off (taken from Howard et al., 2018)

EMG analysis of straight-line sprinting

EMG analysis of sprinting have predominantly been concerned with the hamstrings, quadriceps and gluteals. The following section will outline EMG-results of the hamstrings, quadriceps, and gluteals during straight-line sprinting.

Hamstrings timing and level of activation

The hamstrings consist of the semimembranosus, semitendinosu*s*, and the biceps femoris. The hamstrings are active through the whole stance phase (early and late stance phase), and in the late swing phase to initial contact is made (Higashihara et al., 2010; Pinniger et al., 2000; Yu et al., 2008). The hamstrings are the first muscle group to be activated in the late swing phase (Higashihara et al., 2010). Thus, hamstring power may have a crucial role in reducing the time of this phase. Further, the hamstrings are increasingly activated with increased speed (Albertus-Kajee et al., 2011; Bartlett et al., 2014; Higashihara et al., 2010; Kuitunen et al., 2002; Kyrölainen et al., 2005; Mastalerz et al., 2012; Nummela et al., 1994). Maximum activation of biceps femoris and semimembranosus occurs in the late swing phase and early stance phase, whereas the activation in the late swing phase is up to three times greater than in the late stance and early swing phase (Yu et al., 2008). Further, semitendinosus is activated more than biceps femoris during the mid-swing phase, and peak activation occurs earlier in semitendinosus compared to biceps femoris during the late swing phase (Higashihira et al., 2010).

Being able to suppress braking force in the early stance phase is crucial for achieving greater acceleration and maintaining maximum speed (Nagahara et al., 2018). Thus, as the hamstrings attain peak activation during the early stance phase, eccentric hamstring strength is crucial to be able to suppress the braking forces in this phase. Morin et al., (2015) found a significant relationship between horizontal ground reaction force and the combination of biceps femoris EMG activity during the late swing phase and the knee flexors eccentric peak torque. The subjects who produced the greatest amount of horizontal force were both able to highly activate their hamstring muscles just before initial contact and present high eccentric peak torque capability. These results indicate that the hamstrings are more important at higher, compared to lower, speeds, and that eccentric hamstring strength is most important.

Quadriceps timing and level of activation

The quadriceps consist of the vastus lateralis, vastus medialis, vastus intermedius, and the rectus femoris. Rectus femoris has two clear bursts of activity in the swing phase, one in the early and one in the late swing phase. Vastus lateralis is also active in the late swing phase (Pinninger et al., 2000). Further, Nummela et al. (1994) observed a significant increase in rectus femoris activity in the braking phase. In addition, rectus femoris also contracts eccentrically for hip extension and knee flexion in the early swing phase. Further, it is activated as the leg extends in preparation for ground contact in the late swing phase (Howard et al. 2018), and activity in this phase increases with increased speed (Kuitunen et al. 2002). Mero & Komi (1987) concluded that Rectus femoris is more important as a hip flexor than as a knee extensor. Furthermore, Morin et al. (2015) showed that, during acceleration, the vastus lateralis was significantly more activated than the biceps femoris, rectus femoris and gluteus muscles in the late stance phase, while it was significantly more activated than the biceps femoris and rectus femoris over the entire stance phase. This suggests that the quadriceps are highly important in the acceleration phase as it reaches higher peak activation than the hamstrings in that phase. Thus, an exercise regimen targeting the quadriceps may be more effective than a hamstring exercise in improving acceleration.

Gluteals timing and level of activation

The gluteals consist of gluteus maximus, gluteus medius, and gluteus minimus. The gluteus maximus is activated in the early stance phase and during the late swing phase, whereas peak activity occurs at foot strike (Bartlett et al., 2014; Kyrölainen et al., 2005). Morin et al., (2015) found that the gluteus muscles are significantly more activated in the early stance phase than the biceps femoris during acceleration. When looking at the entire stance phase as one phase, although not significant, the gluteus was activated to a larger degree than the biceps femoris and rectus femoris during the initial acceleration phase (first ten steps). Moreover, gluteus horizontal force was also significantly correlated with performance in the initial acceleration. This suggests that the gluteals are more important than the biceps femoris and rectus femoris in the acceleration phase, and a training regimen targeting the gluteals should therefore be appropriate to improve this phase.

Biomechanical and EMG analysis of COD sprinting

COD-speed can be defined as the ability to dynamically decelerate, change movement direction, and start accelerating again (Jones et al, 2008). Thus, it requires both deceleration and acceleration. COD sprinting is based on the same principles as explained above for straight-line sprinting. However, the component that distinguishes those two types of sprinting is the braking of forces when changing direction. Hader et al., (2014) found that there was a greater rate of decrease in EMG activity in the muscles involved in COD sprinting compared with straight line sprinting when performing RSs. This indicates a faster rate of net inhibition of the motor neuron pool during COD tasks compared to straight-line sprinting. Furthermore, EMG analysis from COD sprinting show that the hamstrings are the key musculature in the braking movement as they eccentrically absorb the forces when changing direction (Brughelli et al., 2008; Chaouachi et al., 2012; Jones et al., 2009). However, COD sprinting also requires concentrically work by the quadriceps when accelerating after breaking (Coratella et al., 2018). Thus, this indicates that quadriceps and hamstrings may be equally important in COD sprinting. However, the kinetic energy of a non-rotating object of mass traveling at a speed is 0.5·mass·velocity squared. That is, the kinetic energy of an object is directly proportional to the square of its speed. Thus, for a twofold increase in speed, the kinetic energy will increase by four, and for a fourfold increase in speed, the kinetic energy will increase by 16. This means that faster players with greater body mass must counteract greater kinetic energy when changing direction. A 65 kg player running at 7 $m \cdot s^{-1}$ must counteract a kinetic energy equal to 1593 Joule, while a 75 kg player running at the same speed must counteract kinetic energy equal to 2109 Joule. Therefore, this means that faster and/or heavier players need to be a lot stronger to counteract the kinetic energy when breaking in COD sprinting, which requires substantial hamstring strength. Overall, this indicate that quadriceps, gluteals and hamstrings are important in COD sprinting, but the hamstrings are more crucial in the braking phase.

Exercises to improve sprint performance

The biomechanics of sprinting and the EMG-activity during sprinting indicate that the quadriceps and gluteals are more important than the hamstrings in the acceleration phase, whereas the hamstrings seem to be crucial in the later phases of the sprint. Regarding COD sprint performance, the hamstring muscles are important in the deceleration phase because it is prominent in absorbing the kinetic energy when changing direction, while the quadriceps and gluteals are important in the acceleration phase because this musculature is predominant in this phase. Thus, all three muscle groups seem to be important in COD sprinting. Based on this, the HBS and Nordic Hamstring (NH) could be two suitable exercises to improve sprint performance (illustration of the exercises can be seen in figure 2 and 3). The HBS is a vertically loaded exercise performed to 90° knee angel which mainly target the quadriceps, but also the gluteals (Schoenfeld, 2010; Garcia et al., 2019). Thus, this exercise could be suitable to improve sprint speed, especially in the acceleration phase, and also COD speed. On the other hand, the NH target the hamstrings eccentrically and could be more suited to improve speed closer to top speed, as well as COD speed. Importantly, van den Tillaar, (2017) compared seven different hamstring strengthening exercises and found that the NH exercise produced the greatest activation in all hamstring muscles, as well as reaching peak activation at the same angles as peak activation during sprinting. Thus, this should be the most relevant exercise to improve eccentric hamstring strength.

Figure 2 Illustration of the half-back squat: stand with feet at approximately shoulder width, go slowly down in eccentric phase, stop at 90° and perform a maximal concentric action until returning to the starting point.

Figure 3 Illustration of the Nordic hamstring: A) Starting position; with the feet locked and held in position, B) lean forward with straight hips and back and hands to chest, until unable to hold C) release and absorb forces with the hands in an eccentric push-up motion and return to the upright starting position with a concentric push-up motion

The effect of HBS and NH on sprint performance

HBS

To date, four studies have examined the effect of HBS MST on sprint performance (Chelly et al., 2009; Helgerud et al. 2011; Rønnestad et al. 2008; Rønnestad et al. 2011). Helgerud et al. (2011) observed the effect of two weekly HBS MST sessions for 8 weeks (4 sets and 4 repetitions, 85% of 1RM) on elite senior male soccer players and showed significant increases in performance from 0-10 m (3.2%, 0.06 s, $p < 0.001$), but not on 10-20 m sprint time (0.8%, 0.01 s slower, no p value given). Looking at the individual sprint times, some subjects had large decrements from 10-20 m, while others had large improvements. This may indicate that the response of such training is differing between individuals. Importantly, Helgerud et al. (2011) did not include a control group (CG) and the study was conducted in the pre-season. Thus, it is not possible to conclude whether the changes in performance were caused by seasonal changes in soccer training or by the HBS training. Furthermore, Rønnestad et al., (2011) improved 40 m sprint (1.8%, 0.1s, $p < 0.05$) in elite senior male soccer players after performing HBS two times per week for 10 weeks. However, they only trained with the MST principles from week 7 to 10 (3 sets of 4-6RM). In addition, no split times were measured, and the study was conducted in the pre-season without any control group. Limiting the usefulness of the study results. Rønnestad et al. (2008) showed a 0.08 s improvement in 40 m sprint in professional male soccer players after a 7-week HBS intervention (two times per week), with

0.03 s of the improvement observed from 0-30 m, 0.03 s from 10 to 30 m, and 0.01 s from 30 to 40 m (Rønnestad et al. 2008). However, the results were not significantly higher than the CG. In addition, the results in Rønnestad, (2008) should be interpreted with caution as a hip flexion exercise was included in the training program *"because it has been indicated that this exercise is important for improvement in sprint performance"(Rønnestad et al., 2008).* In fact, Dean et al., (2005) investigated the effect of the hip-flexion exercise used in Rønnestad, (2008) on untrained men and females, and improved 40-yard sprint performance with 3.8%. Thus, the effect could be due to the hip flexion exercise. Making the usefulness of this study very limited. Interestingly, Chelly et al., (2009) studied the effect of two weekly HBS MST sessions for 8 weeks in youth male soccer players and observed a 22.7% increase in first step velocity, 7.1% increase in velocity for the first 5 m, and 11.9 % in max velocity. They performed four sets per session (1^{st} set; 7 repetitions, 70% of 1RM, 2^{nd} set; 4 repetitions, 80% of 1RM, 3^{rd} set; 3 repetitions, 85% of 1RM, and 4^{th} set; 2 repetitions, 90% of 1RM). It would have been interesting to see what effect the increased step velocities had on the sprint times. However, this is not possible as no sprint times are given. In summary, these results indicate that HBS may improve both acceleration and speed in the phases up to 40 m, but that the largest improvements occur in the early phases of the sprint. However, the results in these studies are not valid and reliable due to many limitations in the research design. Thus, no conclusions can be made. It is evident that there is a need for studies in this field with an appropriate research design. Future studies should include CGs that that avoid any other exercises that may improve sprint performance, a better standardized MST training method with only the HBS included, as well as measuring several split times to investigate in what phases of the sprint the effect of HBS MST occurs.

NH

Four studies have examined the effect of NH on sprint performance (Ishøi et al. 2018; Krommes et al. 2017; Siddle et al., 2009; Suarrez-Arrones et al. 2019). All the NH studies have used similar training protocols, where the NH group are training with their own bodyweight throughout the whole intervention, starting with 2 sets of 5 repetitions and increasing the sets and/or repetitions every week, ending in three sets of 8-10 repetitions. Siddle et al. (2019) improved 10-m sprint performance in amateur soccer and rugby players by 3.2 % after 6 weeks 2 weekly of NH training. The improvement was significantly greater than the CG which decreased their performance by 2.6% (-0.06 s vs. +0.05 s, $p = 0.024$). Further, Ishøi et al. (2018) performed an RS test, consisting of 4·6 10 m sprints, with 15 s recovery period between sprints and 180 s between sets. They measured the sprint performance of each 10-meter. The improvements in the NH group (2.6%, -0.045 s) on the first 10-m sprint was significantly higher (p = 0.005) compared to the CG (0.1 %, +0.002 s). Although not significant, the last sprint improved by 3.2% in the NH group compared to a 0.4% decrease in performance for the CG (-0.06 s vs. 0.08 s, p = 0.094), whereas the total time on the RS test improved by 1.8% in the NH group compared to 0.3% improvement in the CG (-0.798 s vs. -0.149 s, p = 0.056). Thus, they showed that the 10-week NH intervention improved both the first 10 m sprint time and the total time on a RS test in amateur soccer players. Further, the NH group in Krommes et al. (2017) improved 5- and 10-m sprint performance by 9.4% (-0.08 s) and 5.8 % (-0.09 s) whereas the CG decreased their performance by 3.2% (5m: + 0.02 s, 10m: +0.05 s) in both 5 and 10 m. Surprisingly, the NH group showed a decrement in performance of 2.4% (+0.09 s) on 30-m sprint and a 7.4% decrement (+0.18 s) on 10-30 m split time. In comparison, the CG in the same study reduced their 30-m sprint performance by 3.9% (+0.15 s) and 4.5% (+0.10 s) on 10-30 m split time. The authors states that they did not conduct any statistical analysis because of a low number of participants, distinct outliers, and no pre-determined level of statistical power. In addition, the pre-test was conducted after the last game of the season in November 2008, while the intervention started in January 2009 after a long break from soccer and post-tests was conducted in the last week of March. Thus, due to the poor research design and no statistical analysis conducted, no conclusions nor suggestions can be made regarding the effect of NH on sprint performance in this study. Nevertheless, Suares-Arronez (2019) conducted an NH intervention in two different groups of junior professional soccer players and investigated the effect on 5-, 10- and 20-m sprint performance. Three teams were used in the study. One team functioned as NH group 1 which had some previous history of NH training (randomly exposed to the exercise through some training sessions), whereas the second team functioned as NH group 2 and had large history with the NH. The third team was used as a CG. All three groups improved sprint performance on 0-5 m, 0-10 m, and 0-30 m. However, no differences between the groups were observed. The intervention groups only performed 1.5 NH session per week in mean, whereas the other studies in this review have conducted 2-3 sessions per week. In addition, the CG completed training that included non-specified neuromuscular training. Therefore, there may have been large differences in the daily additional training (i.e. soccer training, intensity of training) conducted by each team, and the neuromuscular training of the CG could may have led to improvements as well. Overall, no conclusions can be made, and the summarized studies highlight the need for NH studies with a more appropriate research design.

The effect of HBS and NH on COD sprinting

Surprisingly, no research has studied the effect of HBS on COD sprint performance. However, Wisløff et al. (2004) found a significant moderate correlation between HBS 1RM and a shuttle run test ($r = 0.68$, $p < 0.02$). Other studies have failed to show a significant association or effect (Young et al., 2012; Brughelli et al., 2008; Jones et al., 2009; Chaouachi et al., 2012). On the other hand, Siddle et al. (2019) is the only study to test the effect of NH on COD sprint performance. They showed that 6 weeks of NH training 2 times per week improved COD sprint performance by 2.7% (0.12 s, $p = 0.003$) in amateur soccer and rugby players. Other research shows an association between eccentric hamstring strength and COD speed (Chaouachi et al., 2012; Jones et al., 2009), and it is suggested that the hamstrings are key to absorb the kinetic energy when changing direction (Brughelli, et al., 2008; Chaouachi et al., 2012; Jones et al., 2009). Therefore, it is fair to suggest that the NH exercise should be appropriate for improving COD performance. However, due to the lack of studies investigating the effect of either NH or HBS on COD sprint performance individually, this should be investigated in future studies.

In summary, no studies have investigated the effect of HBS and NH on sprint performance in the same study. However, when summarizing the results of the HBS and NH studies it is revealed that the NH exercise provided almost double magnitude changes on 10-m sprint performance (4.54% vs. 2.45%), and almost three times greater improvement on 20-m sprint performance (4.5% vs. 1.6%), compared to HBS. Other relevant distances such as 5 m, 30 m and 40 m were not possible to compare due to only some distances being measured in each study. However, the NH studies were conducted on senior and youth male amateur and semi-professional players, while the HBS studies were performed on senior male professional and semi-professional players. It is expected that lower level and younger individuals will attain greater gains compared to higher levels and older individuals. There are also several flaws in the research design for both the HBS and NH studies, such as no CG or poor choice of CG, the CG performing neuromuscular training, other exercises implemented in the intervention group, few participants, and conducting pre-testing in the start of pre-season. In addition, no studies measure enough split times to manifest in what sprint distances (i.e. 0-5 m, 0-10 m, 10-20 m, 20-30 m, 30-40 m) the exercise possibly leads to changes in performance. Thus, it is not possible to make a conclusion from these studies. However, due to the big differences between the effect of the HBS and NH on sprint performance, it is interesting to study and compare the exercises in the same study. Lastly, no studies have used the principles of MST when training the NH exercise which is somehow surprising when the hamstring musculature is shown to be highly important in sprinting. Studies that have investigated the effect of NH exercise on sprint performance have increased the amount of repetitions and sets when the player is strong enough to perform 4 repetitions, instead of adding weight and training with MST principles. Although it is not possible to perform the exercise with maximal intended velocity because it is an eccentric exercise, adding weight and training with 3-5RM may lead to greater increases in strength and possibly sprint performance.

Overall, based on todays knowledge it is not possible to confidently design appropriate training programs to improve sprint performance based on individual needs. One player may need to improve acceleration, while another may need to improve top speed or change-in-direction-speed. If research can better manifest what phases of the sprint the individual strength exercises improve, it will be easier to improve sprint performance based on the athletes' needs without having to train multiple exercises. To do so, there is a need to compare the effect of the exercises in the same study and measure straight forward sprint with split times at 5 m, 10 m, 20 m, 30 m, and 40 m, as well as measuring COD sprint. In this way, we can determine whether the exercises lead to improvements in the phases where the relevant musculature seems to be more important (i.e 0-10, 10-20, 20-30, or 30-40 m). This may give important insight and understanding for fitness coaches in soccer clubs that aim to improve sprint abilities in soccer players, and how to improve each phase of the sprint. Lastly, although NH is an eccentric exercise, it would be interesting to apply the MST principles for this exercise also as MST is a more suitable method to improve maximal strength. This may ultimately lead to greater improvements in sprint performance.

Aim and hypothesis

The aim of this study was to conduct a 9-week MST regimen (2 sessions per week) to compare the effect of the HBS and NH on sprint performance in youth male soccer players, and to determine in what phases of the sprint the exercises will potentially have an effect. Due to the COVID-19 outbreak, Norway went into lockdown two days before the post-test was supposed to be conducted. Therefore, the aim and hypothesis had to be modified. Instead, we aimed to study and compare the correlation between HBS 1RM and different sprint distances with the correlation between NH peak force (PF) and the different sprint distances. In addition, as we were able to complete the strength training period, a secondary aim was to study the effect of the training program on strength, with special focus on the NH training method as this has not been conducted before.

We hypothesized that *1)* HBS 1RM will correlate higher with sprint performance on 0-10 m, compared to distances after 10 m, whereas NH PF will correlate higher with sprint performance on the later stages of the sprint (i.e. after 10 m) compared to the first 10 m, *2)* HBS 1RM will show higher correlations than NH PF with 0-20 m sprint time, and NH PF will correlated better than HBS 1RM with 20-40 m sprint time*, 3)* that both HBS 1RM and NH PF will strongly correlate with COD sprint time, and *4)* that the HBS MST will lead to significant gains in strength, whereas training NH with MST principles will lead to greater gains in NH PF compared to the NH training methods used in existing research.

METHOD

Due to the COVID-19 outbreak the post-tests were not allowed to be conducted. However, the methods are described as planned so the study design can be replicated in future studies. A Schematic illustration of the experimental procedures are presented in figure 4

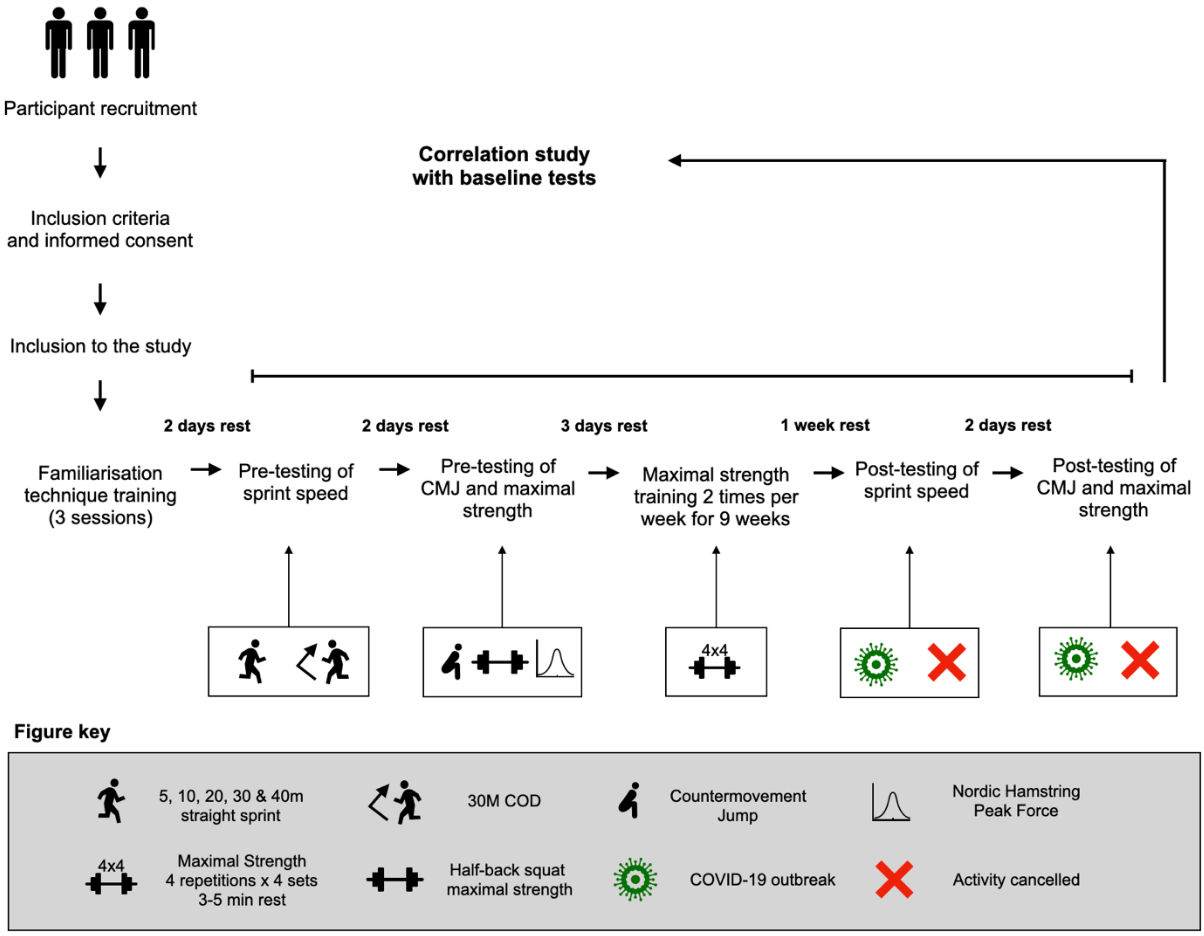


Figure 4 Schematic illustration of the experimental procedures

Subjects

Twenty-three youth players from a Norwegian 1st division professional soccer club volunteered to participate in the study. This study used players from two different teams in the same club; U20's (16-19 years) and U17's (14-16 years). The players were randomly allocated to either a HBS group (n = 8, 15.0 ± 1.4 years, 176.7 ± 10.8 cm, 62.9 ± 11.8 kg) or a NH group (n = 9, 15.4 ± 1.2 years, height: 176.7 ± 6.2 cm, mass: 62.9 ± 8.3 kg). The NH group performed the NH exercise, and the HBS group performed thee HBS exercise. There was no significant difference between the groups in anthropometric parameters (table 1). The inclusion criteria were that the players had no previous experience with systematic strength training in the lower limb. Both teams had three soccer training sessions per week throughout the whole intervention period. The age-matched CG consisted of players from a team playing in the same division as the intervention groups. This was to avoid that the CG was involved with the intervention groups, which possibly can result in players from the CG implementing the HBS and NH programs in their own training. For the CG, no lower limb strength training was allowed. However, the CG is not relevant in this study due to post-tests being cancelled in a result of the COVID-19 outbreak, and all their data are excluded from this thesis. All participants and their legal guardians signed a written informed consent.

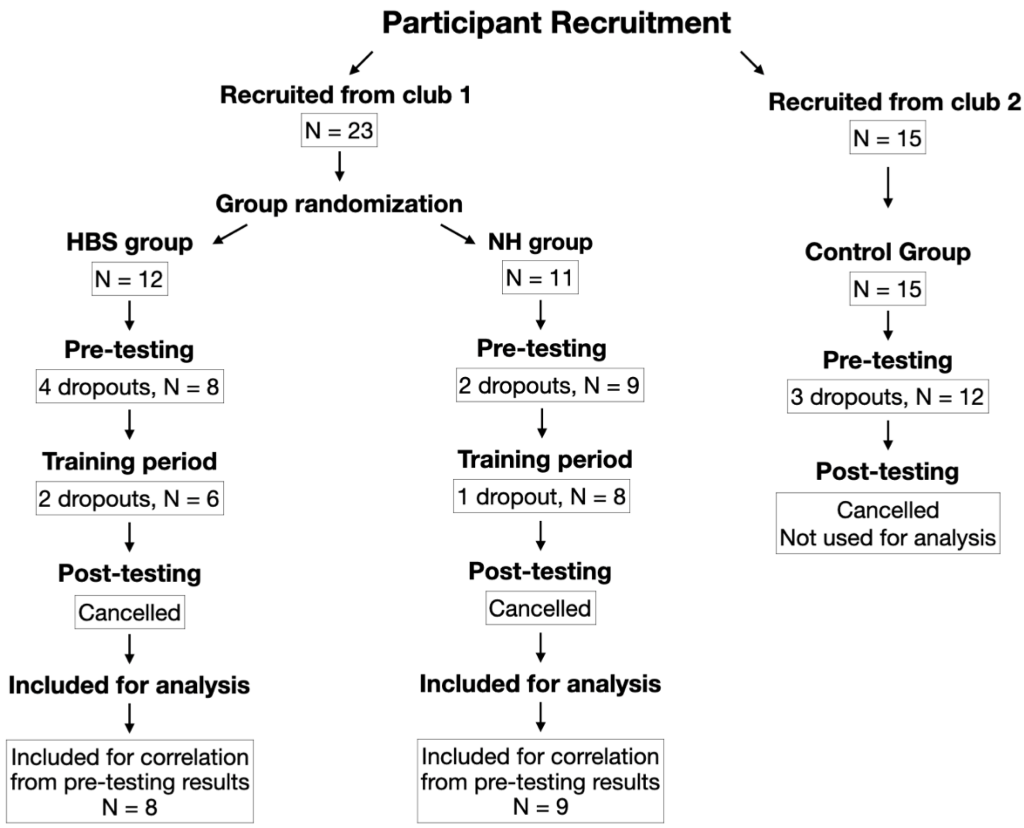


Figure 5 Flow diagram of participant enrolment, allocation, and analysis

Table 1 Anthropometric characteristics of subjects

	HBS (n = 8)	NH (n = 9)
Age (years)	15.0 ± 1.4	15.4 ± 1.2
Height (cm)	176.7 ± 10.8	176.7 ± 6.2
Weight (kg)	62.9 ± 11.8	62.9 ± 8.3

Data are presented as mean ± standard deviation (SD).
HBS, Half-back squat; NH, Nordic hamstring, n, number of participants

Testing and training procedure

Both training groups completed three familiarization sessions in their given exercise. Four testing days was to be performed, two pre-testing days and two post-testing days similar to the pre-tests. However, post-tests got cancelled due to the COVID-19 outbreak. All participants were told to avoid strenuous activity for the last 24 hours before testing days. No intake of caffeine was allowed the last 24 hours before testing. All strength training sessions for both groups were performed before or after the soccer sessions, in indoor training facilities (Ranheim Indoor Arena, Trondheim) situated next to the soccer training pitch. A minimum of 18 strength sessions (2 sessions per week for 9 weeks) had to be completed. The project was conducted in the pre-season and all three teams performed 2-3 soccer sessions per week.

Familiarization

The familiarization sessions were performed to ensure optimal technique before maximal strength testing and the training intervention. The HBS group and NH group did only receive technique training in their given exercise. The NH group performed 4 sets of 4 submaximal repetitions in each familiarization session. The HBS performed 4 sets of 12 repetitions. The reason for performing fewer repetitions in the NH exercise was because it is an eccentric exercise which is harder to perform.

Test day 1

On this test day a 40 m straight-line sprint test with measures at 5, 10, 20, 30, and 40m and a 30 m COD-sprint with four 90° turns was performed. All sprint measurements were performed indoors at artificial grass suited for soccer play (Flatåsen Artifical Indoor Arena, Trondheim). Straigth-line sprint performance was recorded by photocells (Brower Timing, Fairlee, Vermont, USA), and COD sprint performance was recorded by a wireless system of interconnected light powered sensors (FitLight Trainer, Sport corp. Ontario, Canada). The Brower timing system is not as accurate as laboratory systems where photocells are mounted to the wall, but the system is of a good use in practice to monitor changes in running speed for lower level athletes as the errors associated with test-retest are small and the limits of agreement are small as well (Shalwfali et al. 2012). Regarding the FitLight system, this was used due to its easy set up when performing COD sprint tests as you only need one sensor per measurement, and not two sensors as needed with the Brower timing system used for the straight-line sprint test. However, no research has documented its accuracy and reliability.

40 m straight-line sprint

The subjects were instructed to use artificial turf soccer shoes, training socks, shorts and t-shirt. First, the participants performed a 20-minute general and specific warm-up/activation protocol guided by a researcher. Then, all participants performed three 40 m straight-line sprint trials with three minutes rest in between the sprints. Photocells were placed at 5 m, 10 m, 20 m, 30 m and 40 m. Players started from a static position with the left foot in front, 30 cm behind the first photocell, and time recording started when the photocell beam was intercepted by the trunk. Subjects were instructed to start from a "ready-set-go" signal and were informed to perform the sprint with maximal effort. The best result from each split time was used for analysis, independent of trial.

Figure 6 Brower timing system (left) and FitLight system (right) used for 40 m straight-line sprint and COD sprint testing, respectively.

COD sprint test

After the straight-line sprint was performed, the participants were given a 10-minute rest before performing the COD-sprint test. The COD sprint test consisted of four 90° cuts (two to each side). These angles were chosen because around 84% of all CODs in soccer occur in angles between 0-90° (Bloomfield et al., 2007). The Fit Light sensors was placed on a pole 1 m above the ground. The same starting procedures as in the 40 m straight-line sprint test was used. All participants performed three trials with 3 minutes in between each sprint. Only the best sprint time measured at the last sensor was used for analysis due to a measurement error at some of the split times. An explanation of the COD-sprint test set-up can be seen in figure 7.

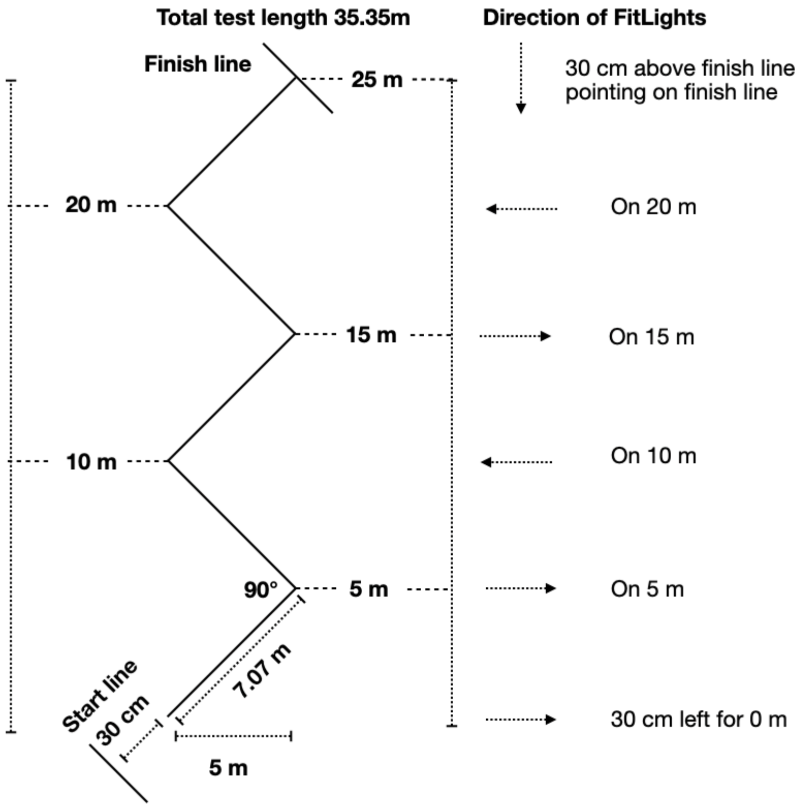


Figure 7 Schematic illustration of the COD-sprint test

Test day 2

After 48 hours rest test day 2 was conducted. On this test day countermovement jump and maximal strength measures was performed. The subjects were instructed to use indoor training shoes, socks, shorts and a t-shirt.

Vertical jump testing

First, the subjects performed a standardized warm-up including 10 min running followed by a five-minute specific jumping warm-up consisting. Jumping height was measured by a countermovement jump performed on a contact mat (Fusion Sport, SmartJump, Australia). The players were instructed to keep their hands on their hips during the jump. The best jump of three attempts was recorded and included in the analysis. The subjects had 2 minutes rest between each jump. The repeatability of the CMJ has been reported with a coefficient of variation of 1.6 % (Cormack et al. 2008).

Figure 8 Jump mat used for CMJ height testing

Maximal strength and peak force testing

The participants were given 5 minutes rest after the jumping test before the maximal strength testing started. The participants performed the maximal strength testing in their given exercise only. The HBS group tested HBS 1RM and the NH group tested NH PF.

For HBS 1RM testing, participant was instructed to stand with feet at approximately shoulder width, go slowly down in eccentric phase, stop at 90° and perform a maximal concentric action until returning to the starting point (see figure 2). Subjects performed a standardized specific warm-up consisting of different loads and repetitions based on their estimated 1RM (based on weights used in the familiarization sessions); 10x50%, 5x60%, 3x70%, and 2x80% of estimated 1RM. The first 1RM trial was performed with a weight corresponding to 5% under the estimated 1RM. For the 1RM trials, each successful lift where followed by a 5 kg increase in weight until the attaining the maximal level and/or failure were achieved. A 3 to 5-minute rest was given between each attempt and the heaviest lift was recorded.

NH PF was tested using a custom-made testing device (Arnfinn Sira, NTNU, Trondheim, Norway) that measures eccentric hamstring strength during the NH exercise. The testing device sensors and accuracy is similar to the NordBord (VALD Performance, Queensland, Australia) which is shown to provide reliable measures of eccentric hamstring strength (CV = 8%) (Opar et al., 2013). The participants were kneeling on a padded board with their ankles placed in two individual hooks (superior to the malleoli) attached to force cells. The participants were instructed to keep their hands at chest level to brace for when they reach the point of failure and to keep a straight line from shoulder through to the knee. In addition, they were told to control the movement for as long as possible, but to not stop the forward motion completely at any point. The participants had already performed a 10-minute warm up before the CMJ test. Before conducting the NH PF test, three sets of four submaximal NH repetitions were performed as a warm-up. Then, they were given three maximal attempts with two minutes rest in between.

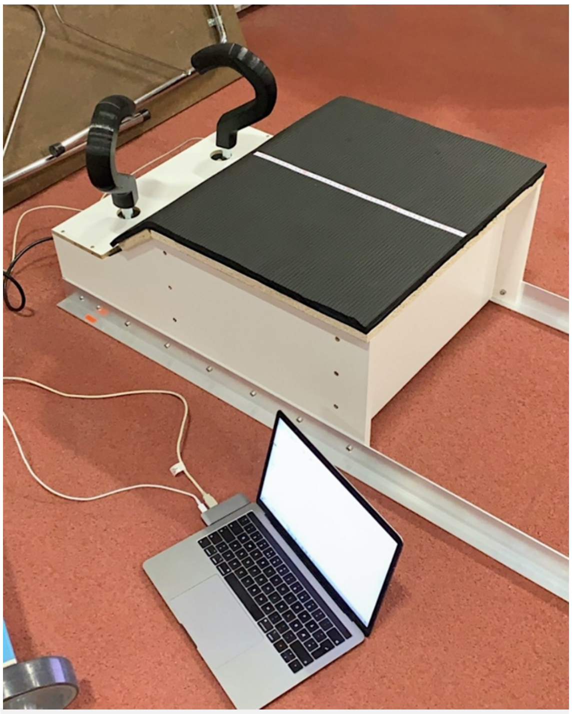


Figure 9 The custom-made NH testing device used for measuring NH PF

The trial was accepted when a PF value followed by a rapid decline was evident. NH eccentric PF was calculated as the mean PF of left and right legs from the best trial.

Training procedures

The HBS group trained with the same technique as used in the 1RM test and started to train with 85% of their 1RM. Three warm-up sets were performed, followed by 4 repetitions and 4 sets with emphasis on maximal intended velocity in the concentric phase. The load was increased by 5 kg if the participant managed to perform two successful sets with optimal technique. Three to five minutes rest was given between each set. The training was conducted using an Olympic bar and Olympic weights.

The NH group conducted their training in a NH apparatus (Pivot 618, Sportsmaster, Norway), and the same technique as described in the PF testing was used. Participant started to train with their own bodyweight as no participants were able to perform the whole movement in the exercise. The protocol included a warm-up of 3 sets of 4 submaximal repetitions, followed by the training consisting of 4 sets of 4 repetitions with maximal effort. A weight plate of 2.5kg were added when the players were able to hold and control the movement all the way for four repetitions and two sets (figure 10). The participant was instructed to hold the weight 5 cm in front of their chest, and drop it to break the fall in a push-up motion when unable to hold any longer. Three to five minutes rest between each set was given.

Figure 10 Illustration of how to hold the added weight when performing the NH exercise in the NH apparatus

Allometric scaling

Comparison of athletes' maximal strength are often provided as relative to body weight ($kg \cdot bw^{-1}$). This is functionally imprecise because 1RM does not increase in direct proportion to body mass in trained individuals (Helgerud et al., 2011). If this method is not used the relative strength of a big athlete will be overestimated and for a smaller person, it will be underestimated. According to appropriate dimensional scaling procedures, comparison of muscle strength between a small and bigger person should be expressed as $kg \cdot bw^{-0.67}$ (Wisløff et al., 1998). Therefore, this article will use $kg \cdot bw^{-0.67}$ for HBS 1RM and $N \cdot bw^{-0.67}$ for the NH PF values. All discussions will be based around the scaled values ($kg \cdot bw^{-0.67}$ and $N \cdot bw^{-0.67}$). However, the analysis of the non-scaled results is presented for three reasons; 1) few studies use allometric scaling in their analysis, although it is recommended to do so, 2) to give the reader the opportunity to interpret the results by those numbers if preferred, and 3) it is not enough research to conclude how to most correctly interpret the NH PF yet. However, there is no doubt that taller and heavier individuals will attain higher PF in the NH exercise compared to a shorter and lighter individual. Suarez-Arrones et al., (2019) demonstrated that there was a large correlation with players body mass and eccentric hamstring PF. Therefore, the same allometric scaling numbers are used for HBS and NH.

Statistical Analysis

The software program IBM SPSS, version 25.0 (Statistical Package for Social Science, Chicago, IL) was used for the statistical analysis, and figures were created in Excel 2020 for Mac (version 16.53) and prism 8 2020 for Mac (version 8.4.2). Both the HBS and NH dataset was normally distributed. Therefore, correlations between the investigated variables were analyzed with the Pearson's correlation test, and a paired sample t-test was used on analysis of changes in strength. $P < 0.05$ indicate statistical significance. Correlation coefficients were considered weak for values lower than 0.5, whereas moderate and strong correlation coefficients were used for values larger than 0.5 and 0.7, respectively as suggested by Hopkins et al. (2009).

RESULTS

HBS 1RM vs. NH PF sprint correlations

In general, HBS 1RM (kg·bw$^{-0.67}$) correlated better with all sprint distances compared with NH PF (N·bw$^{-0.67}$) (table 1). We observed a border-significant correlation between HBS 1RM (kg·bw$^{-0.67}$) and 5m sprint time (r = -0.69, p = 0.060) but not between NH PF (N·bw$^{-0.67}$) and 5m sprint time (r = 0.49, p = 0.176). The correlations between HBS 1RM (kg·bw$^{-0.67}$) and 0-20m (r = -0.86, p = 0.006) and 20-40 m (r = -0.91, p = 0.002) sprint times were 18.6% and 5.5% higher than the corresponding correlations between NH PF (N·bw$^{-0.67}$) and sprint times (20m: r = -0.70 , p = 0.035, 20-40m: r = -0.86, p = 0.003). Furthermore, we observed a 13.6% better correlation between HBS 1RM (kg·bw$^{-0.67}$) and COD sprint time (r = -0.88, p = 0.004) when compared to the correlation between NH PF (N·bw$^{-0.67}$) and COD sprint time (r = -0.76, p = 0.018) (Table 2). Table 3 presents correlations between strength and time spent on the different sprint distances, sorted by correlation strength. Mean sprint time are presented in table 4.

Table 2 Sprint and jump-height correlations with HBS 1RM (kg·bw$^{-0.67}$) and NH PF (N·bw$^{-0.67}$), and absolute HBS 1RM (kg) and NH PF (N)

Measure	HBS 1RM (kg·bw$^{-0.67}$)		NH PF (N·bw$^{-0.67}$)		Diff (%)	HBS (kg)		NH PF (N)	
	R value	P value	R value	P value		R value	P value	R value	P value
COD	-0.88	0.004**	-0.76	0.018*	13.6	-0.86	0.007**	-0.79	0.011*
0-5m	-0.69	0.060	-0.49	0.176	29.0	-0.81	0.016*	-0.64	0.062
0-10m	-0.77	0.026*	-0.65	0.058	15.6	-0.84	0.009**	-0.75	0.019*
0-20m	-0.86	0.006**	-0.70	0.035*	18.6	-0.91	0.001**	-0.74	0.023*
0-30m	-0.89	0.003**	-0.77	0.016*	13.5	-0.93	0.001**	-0.80	0.010*
0-40m	-0.90	0.003**	-0.80	0.010*	11.1	-0.93	0.001**	-0.80	0.010*
10-20m	-0.92	0.001**	-0.69	0.039*	25.0	-0.95	0.001***	-0.65	0.060
20-30m	-0.93	0.001***	-0.85	0.004**	8.6	-0.92	0.001**	-0.83	0.002**
30-40m	-0.86	0.006**	-0.83	0.005**	3.5	-0.90	0.002**	-0.77	0.015*
10-30m	-0.93	0.001***	-0.81	0.008**	12.9	-0.94	0.001***	-0.79	0.011*
20-40m	-0.91	0.002**	-0.86	0.003**	5.5	-0.93	0.001**	-0.83	0.006**
10-40m	-0.92	0.001**	-0.83	0.006	9.8	-0.94	0.001**	-0.79	0.011*
5-10m	-0.75	0.033*	-0.71	0.033*	5.3	-0.72	0.044*	-0.73	0.025*
5-20m	-0.93	0.001***	-0.73	0.025*	21.5	-0.94	0.001**	-0.71	0.032*
5-30m	-0.93	0.001***	-0.80	0.009*	13.9	-0.93	0.001**	-0.78	0.014*
5-40m	-0.92	0.001**	-0.82	0.007*	10.9	-0.94	0.001**	-0.79	0.011*
CMJ (cm)	0.86	0.007**	0.52	0.153	39.5	-0.84	0.009**	0.53	0.141

*, significance at 0.05; **, significance at 0.01; ***, significance < 0.001; 1RM, one-repetition maximum; bw, bodyweight; CMJ, countermovement jump; COD, change of direction; HBS, half-back squat; kg, kilogram; N, newtons; NH, Nordic hamstring; PF, peak force.

Table 3 Sprint and jump-height correlations with HBS 1RM ($kg \cdot bw^{-0.67}$) and NH PF ($N \cdot bw^{-0.67}$), and HBS 1RM (kg) and NH PF (N) (Sorted by R value)

HBS 1RM ($kg \cdot bw^{-0.67}$)				NH PF ($N \cdot bw^{-0.67}$)			
Sprint Distance	R value	P value	R^2	Sprint Distance	R value	P value	R^2
10-30m	-0.93	0.001***	0.87	20-40m	-0.86	0.003**	0.74
5-30m	-0.93	0.001***	0.87	20-30m	-0.85	0.004**	0.73
5-20m	-0.93	0.001***	0.86	30-40m	-0.83	0.005**	0.69
20-30m	-0.93	0.001***	0.86	10-40m	-0.83	0.006**	0.68
5-40m	-0.92	0.001**	0.85	5-40m	-0.82	0.007**	0.67
10-20m	-0.92	0.001**	0.85	10-30m	-0.81	0.008**	0.66
10-40m	-0.92	0.001**	0.84	5-30m	-0.80	0.009*	0.64
20-40m	-0.91	0.002**	0.83	0-40m	-0.80	0.01*	0.63
0-40m	-0.90	0.003**	0.80	0-30m	-0.77	0.016*	0.59
0-30m	-0.89	0.003**	0.79	5-20m	-0.73	0.025*	0.53
30-40m	-0.86	0.006**	0.74	5-10m	-0.71	0.033*	0.50
0-20m	-0.86	0.006**	0.74	0-20m	-0.70	0.035*	0.49
0-10m	-0.77	0.026*	0.59	10-20m	-0.69	0.039*	0.48
5-10m	-0.75	0.033*	0.56	0-10m	-0.65	0.058	0.42
0-5m	-0.69	0.060	0.47	0-5m	-0.49	0.176	0.25

*, significance at 0.05; **, significance at 0.01; ***, significance < 0.001; 1RM, one-repetition maximum; bw, bodyweight; CMJ, countermovement jump; COD, change of direction; HBS, half-back squat; kg, kilogram; N, newtons; NH, Nordic hamstring; PF, peak force.

Table 4 Mean sprint times for each measurement.

	Mean (s) ± SD		
Distance	HBS	NH	HBS+NH
5 m	1.02 ± 0.11	0.99 ± 0.06	1.01 ± 0.08
10 m	1.81 ± 0.15	1.78 ± 0.09	1.80 ± 0.12
20 m	3.15 ± 0.26	3.13 ± 0.16	3.14 ± 0.21
30 m	4.41 ± 0.38	4.39 ± 0.22	4.40 ± 0.30
40 m	5.68 ± 0.49	5.66 ± 0.33	5.67 ± 0.40
COD	9.23 ± 0.35	9.15 ± 0.27	9.19 ± 0.30

COD, Change of direction; HBS, half-back squat; m, meter;
NH, Nordic hamstring; s, seconds; SD, standard deviation.

HBS and correlations with different sprint distances

For HBS 1RM ($kg \cdot bw^{-0.67}$) the correlation with 20-30 m sprint time ($r = -0.93$, $p < 0.001$) was 17.2% higher than the corresponding correlation for 0-10 m sprint time ($r = -0.77$, $p = 0.026$), whereas correlation with 0-40 m sprint time ($r = -0.90$, $p = 0.003$) was 23.3% higher than that observed for 0-5 m sprint time ($r = -0.69$, $p = 0.060$) (Figure 11).

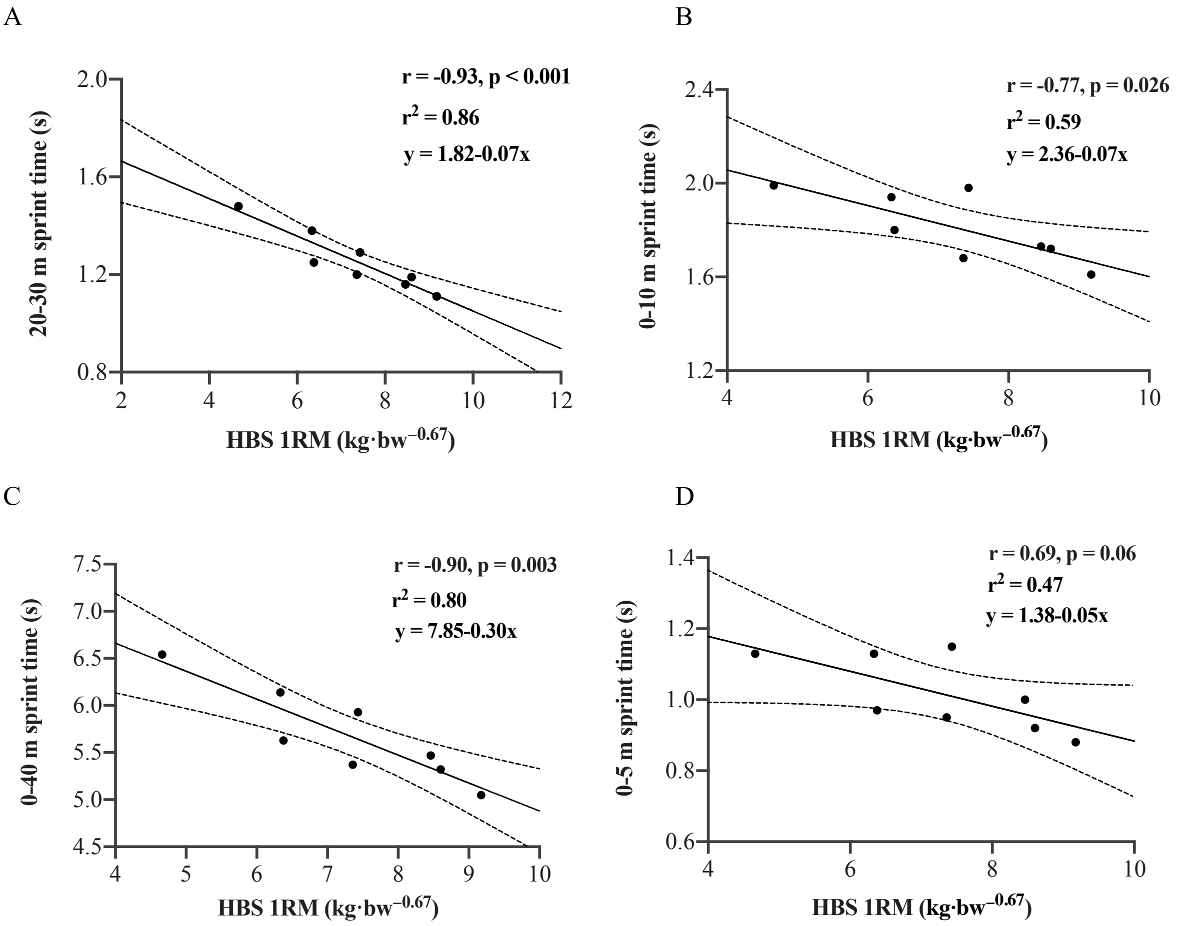
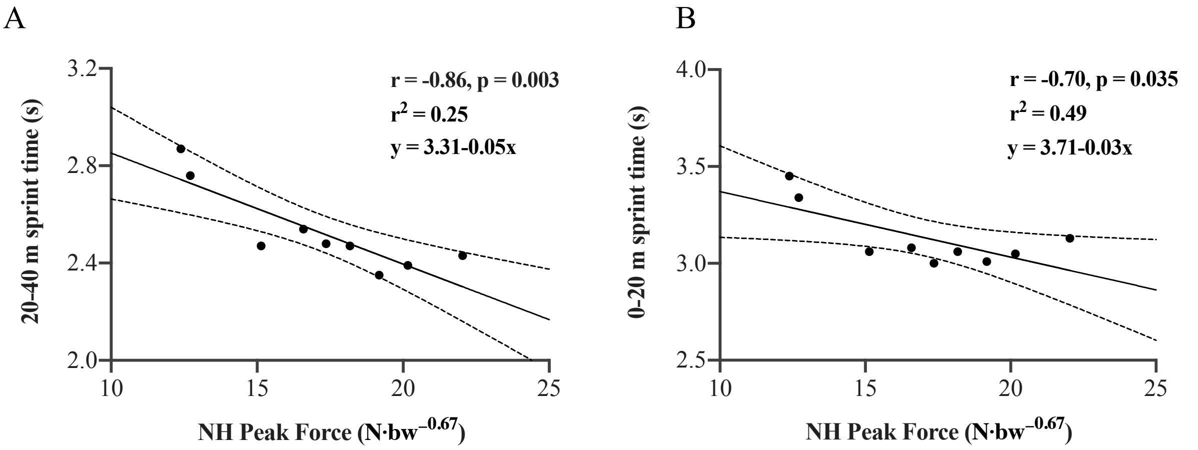


Figure 11 A. Correlation between 20-30 m sprint and HBS 1RM (kg·bw$^{-0.67}$), B. Correlation between 10 m sprint time and HBS 1RM (kg·bw$^{-0.67}$), C. Correlation between 40 m sprint time and HBS 1RM (kg·bw$^{-0.67}$), D. Correlation between 5 m sprint time and HBS 1RM (kg·bw$^{-0.67}$).

NH and correlations with different sprint distances

For NH PF (N·bw$^{-0.67}$) the correlation was 18.6% higher at 20-40 m sprint time (r = -0.86, p = 0.003) compared to that observed at 0-20 m sprint time (r = -0.70, p = 0.035). Similar, the correlation between NH PF (N·bw$^{-0.67}$) and 0-40 m (r = -0.80, p = 0.01) was 38.8% higher than that observed for 0-5 m (r = -0.49, p = 0.176) (Figure 12).



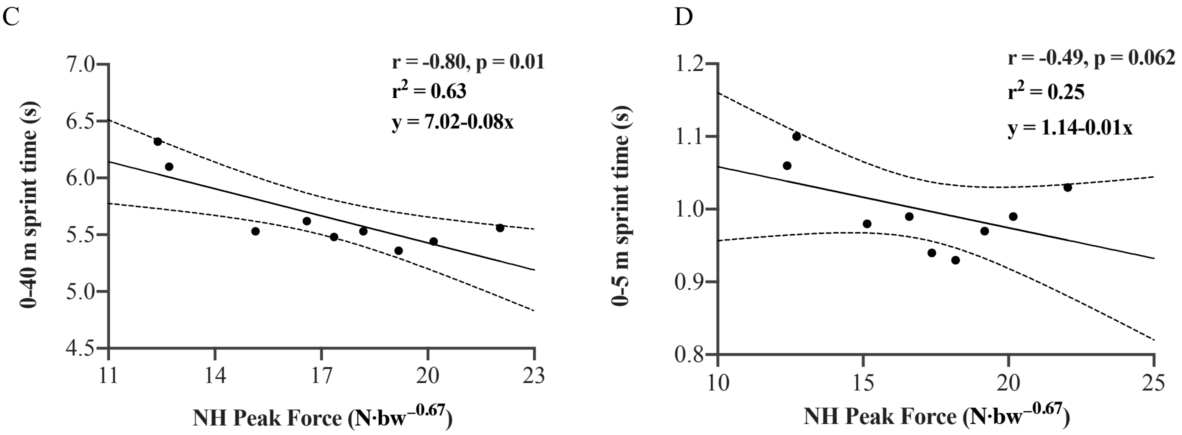


Figure 12 A. Correlation between 20-40 m sprint and NH PF (N·bw$^{-0.67}$). B. Correlation between 20 m sprint time and NH PF (N·bw$^{-0.67}$). C. Correlation between 40 m sprint time and NH PF (N·bw$^{-0.67}$). D. Correlation between 5 m sprint time and NH PF (kg·bw$^{-0.67}$).

COD and maximal strength correlations

The correlation between COD sprint time and HBS 1 RM (kg·bw$^{-0.67}$) (r = -0.88, p = 0.004) was 13.6% higher than the correlation between COD sprint time and NH PF (N·bw$^{-0.67}$) (r = -0.76, p = 0.018) (Figure 13).

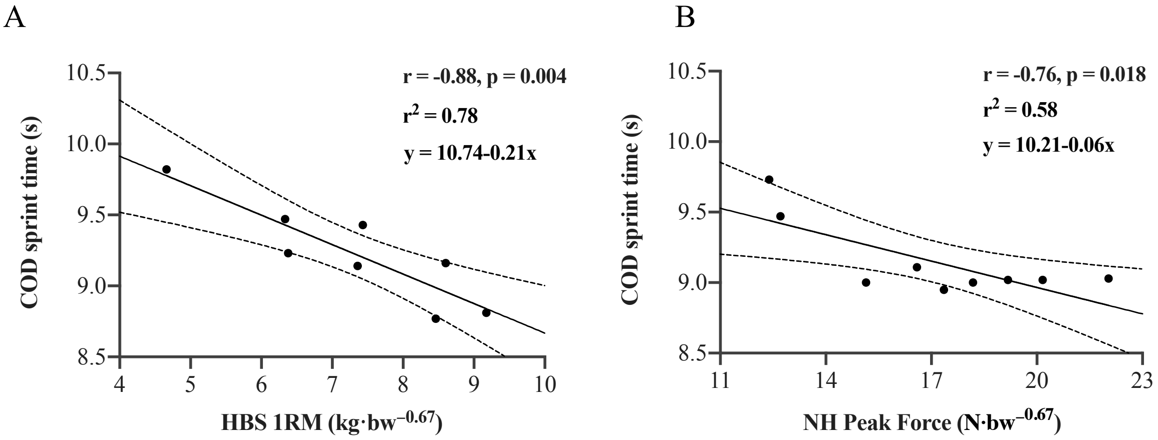


Figure 13 A. Correlation between COD sprint time and HBS 1RM (kg·bw$^{-0.67}$). B. Correlation between COD sprint time and NH PF (N·bw$^{-0.67}$).

CMJ and maximal strength correlations

The correlation between CMJ height and HBS 1RM (kg·bw$^{-0.67}$) (r = 0.84, p = 0.009) was 38% stronger than the correlation between CMJ height and NH PF (N·bw$^{-0.67}$) (r = 0.54, p = 0.153) (Figure 14).

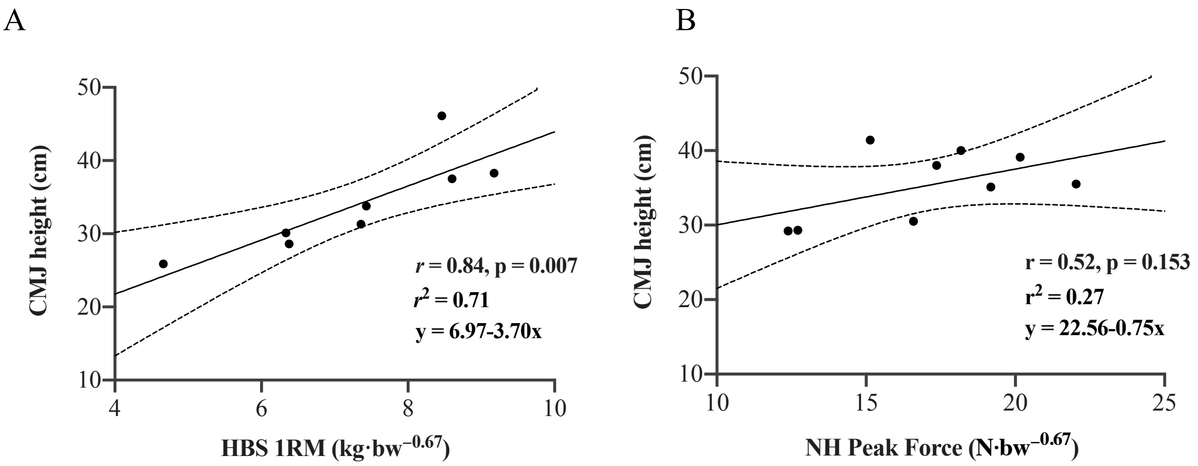


Figure 14 A. Correlation between HBS 1RM (kg·bw$^{-0.67}$) and CMJ. B. Correlation between NH PF (N·bw$^{-0.67}$) and CMJ.

COD and sprint correlations

The COD sprint time correlated 17.2% higher with 0-30 m straight-line sprint time (r = 0.93, p < 0.001), and 16.1% higher with 20-30 m straight-line sprint time (r = 0.92, p < 0.001), compared to that observed at 0-5 m straight-line sprint time (r = 0.77, p = <0.001). Similarly, COD sprint time correlated higher with all other sprint times when compared to 0-5 m (table 5).

Table 5 COD and straight-line sprint time correlations (Sorted by r value)

Sprint Distance	Pearson correlation	P Value	R^2
0-30 m	0.93	0.001***	0.86
0-40 m	0.92	0.001***	0.85
20-30 m	0.92	0.001***	0.84
0-20 m	0.92	0.001***	0.89
10-30 m	0.91	0.001***	0.84
20-40 m	0.91	0.001***	0.82
10-40 m	0.91	0.001***	0.82
5-10 m	0.89	0.001***	0.80
0-10 m	0.89	0.001***	0.80
10-20 m	0.87	0.001***	0.76
30-40 m	0.85	0.001***	0.74
0-5 m	0.77	0.001***	0.59

***, sig. < 0.001

Table 6 CMJ and sprint time correlations (Sorted by r value)

Sprint Distance	Pearson correlation	P Value	R^2
COD	-0.85	0.001***	0.72
20-30 m	-0.73	0.001**	0.53
10-30 m	-0.71	0.001**	0.51
0-30 m	-0.71	0.001**	0.50
5-10 m	-0.70	0.002**	0.49
0-40 m	-0.70	0.002**	0.48
0-20 m	-0.69	0.002**	0.47
10-40 m	-0.68	0.002**	0.47
20-40 m	-0.68	0.003**	0.46
10-20 m	-0.67	0.003**	0.45
0-10 m	-0.66	0.004**	0.44
30-40 m	-0.61	0.009**	0.37
0-5 m	-0.55	0.022*	0.31

*, sig. at 0.05; **, sig. at 0.01, ***, sig. < 0.001

CMJ and sprint correlations

CMJ height correlated strongly and significantly with COD sprint performance ($r = -0.85$, $p < 0.001$), and straight-line sprint performance on 20-30 m ($r = -0.73$, $p = 0.001$), 10-30m ($r = -0.71$, $p = 0.001$), 0-30 m ($r = -0.71$, $p = 0.001$), 5-10 m, and 0-40 m ($r = -0.70$, $p = 0.002$). All other sprint times showed a moderate correlation with CMJ height, whereas the weakest correlation was between CMJ and 0-5 m ($r = -0.55$, $p = 0.022$) (table 6).

Mean speed on the different split times

Analysis of the mean sprint speed on the different split times are presented in figure 15. Players reached top speed after approximately 20 m, as the highest speeds are seen from 20-30 m (1.26 s ± 0.10, 28.73 km/h ± 2.09). Moreover, there is a small reduction in the mean speed from 30-40 m (1.27 s ± 0.11, 28.52 km/h ± 2.25) compared to 20-30 m.

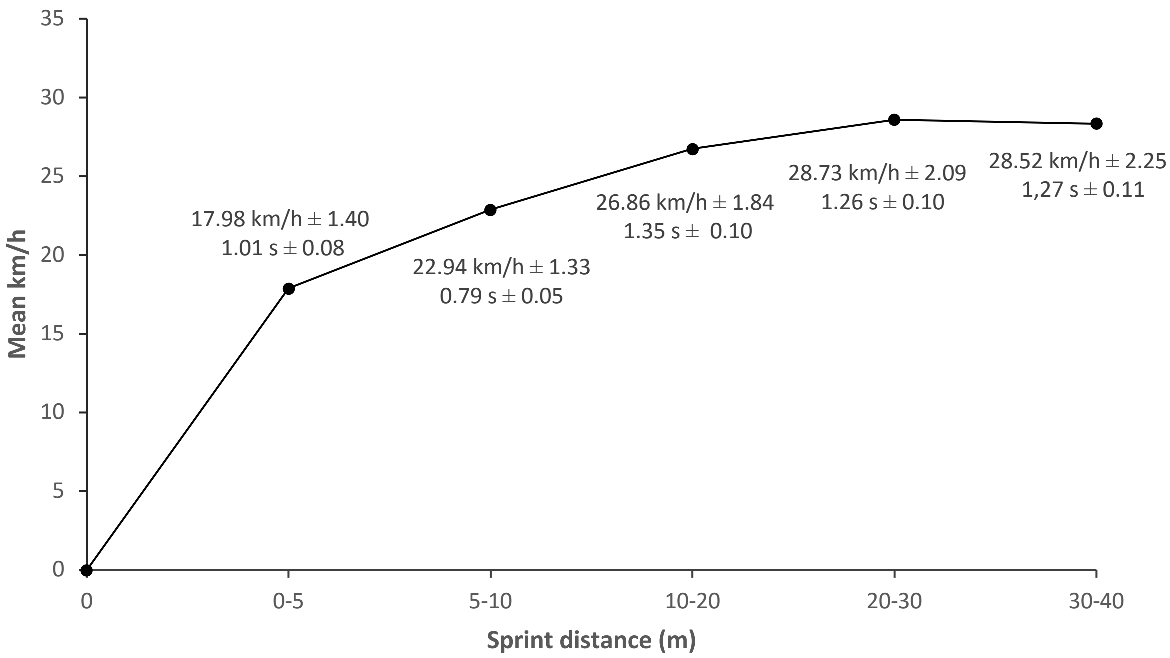


Figure 15 Mean speed (km/h) and sprint time (s) between split distances.

Changes in strength

Participants increase in maximal strength are presented in table 6 (HBS) and table 7 (NH). The HBS group increased their 1RM by 56%, whereas the NH group increased their NH PF by 39%. For the HBS group, the predicted post 1RM is based on the following; participants started to train with 85% of the pre-test 1RM at baseline. Therefore, it is fair to assume that the participants trained with 85% of their 1RM on the last training session. Thus, the post-test 1RM is calculated as 4RM in the last strength training session divided on 85%. For the NH group the predicted PF is calculated based on the following: no participants were able to hold and control the movement all the way down in the NH exercise in the pre-test. The extra weight they trained with the last session is added to the pre-test to find the predicted post-test result. The post-test values for the NH group is therefore possibly underestimated because this is the 4RM weight. However, no participants were able to hold and control the movement in 4 repetitions with the weight trained with (as soon as they are able to do so extra weight would have been added). Thus, the values should be relatively realistic, and this is considered the best way to predict the post-test NH PF. A paired t-test was conducted to investigate whether the changes in maximal strength within the groups were significant.

The HBS dataset ($D6 = 0.158$, $P = 0.877$) was normally distributed. Therefore, a paired samples t-test was used to determine whether the HBS training led to significant increases in HBS 1RM. The data show that there was a significant increase in HBS 1RM from the pre-test (110.83 ± 31.05 kg) to the post-test (168.67 ± 33.71 N), $t5 = -18.902$, $P < 0.001$. (See table 7).

The NH dataset ($D9 = 0.237$, $P = 0.327$) was normally distributed. Therefore, a paired-samples t-test was used to determine whether the NH training led to significant increases in NH PF. The data show that there was a significant increase from the pre-test (274.82 ± 62.64 N) to the post-test (381.09 ± 84.36 N), $t8 = -9.192$, $p < 0.001$. (see table 8).

Table 7 Changes in 1RM from pre-test to post-test for the HBS group

Subjects*	**Training load 1st session**	**Training load last session**	**PF pre-test ($kg \cdot bw^{-0.67}$)**	**Predicted PF post-test ($kg \cdot bw^{-0.67}$)**	**PF pre-test**	**Predicted PF post-test**	**% increase**
1	130	175	8.60	11.80	150	206	37
3	50	100	4.66	9.14	60	118	96
4	80	125	6.34	9.81	95	147	55
5	95	135	7.43	10.73	110	159	44
7	100	155	7.36	11.18	120	182	52
8	110	170	8.46	13.02	130	200	54
Average	94.17	143.33	7.14	10.95	110.83	168.63	56.39***
SD	27.28	28.75	1.47	1.39	31.05	33.83	20.56
Max	130.00	175.00	8.60	13.02	150.00	205.88	96.08
Min	50.00	100.00	4.66	9.14	60.00	117.65	37.25

*, participant 2 and 6 did not finish the training period and is excluded; ***, significance < 0.001; 1RM, one repetition maximum; bw, bodyweight; HBS, half-back squat; kg, kilogram; SD, standard deviation.

Table 8 Changes in NH PF from pre-test to post-test for the NH group

Subject	Training load 1st session	Training load last session	PF pre-test ($N \cdot bw^{-0.67}$)	Predicted PF post test ($N \cdot bw^{-0.67}$)	PF pre-test	Predicted PF post-test	% increase
1	Bw NFR	12.5	19.18	26.66	314.35	436.97	39
2	Bw NFR	7.5	12.71	18.18	171.07	244.64	43
3	Bw NFR	5	20.16	23.68	280.94	329.99	17
4	Bw NFR	15	17.36	26.07	293.27	440.42	50
5	Bw NFR	15	18.18	26.48	322.07	469.22	46
6	Bw NFR	10	12.39	18.74	191.36	289.46	51
7	Bw NFR	12.5	22.04	29.37	368.72	491.34	33
8	Bw NFR	12.5	15.14	22.56	249.92	372.545	49
9	Bw NFR	7.5	16.59	20.92	281.66	355.23	26
Average	Bw NFR	10.83	17.08	23.63	274.82	381.09	39.45***
Std	Bw NFR	3.54	3.26	3.85	62.64	84.36	11.72
Max	Bw NFR	15.00	22.04	29.37	368.72	491.34	51.26
Min	Bw NFR	5.00	12.39	18.18	171.07	244.64	17.46

***, significance < 0.001; 1RM, one repetition maximum; bw, bodyweight; N, newtons; NH, Nordic hamstring; NFR, not full range; PF, peak force; SD, standard deviation.

Difference in sprint times for strong vs. weak players

To underpin the correlations between maximal strength and sprint performance, an analysis of the sprint times for strong players vs. weak players was conducted. The players were divided into two groups: strong (above the mean 1RM value) and weak (below the mean 1RM value). The same was done for the NH group based on the NH PF.

For the HBS group, the players categorized as strong was significantly faster at 20-30 m (p = 0.028), 5-30 m (p = 0.029), 5-40 m (p = 0.030), 20-40 m (p = 0.032), 5-20 m (p = 0.032), 10-30 m (p = 0.035), 0-40 m (p = 0.047), 30-40 m (p = 0.047), and 10-20 m (p = 0.048). Further, although not significant, the strong group was faster than the weak group at 0-30 m (p = 0.053), 5-10 m (p = 0.065), COD (p = 0.074), 0-20 m (p = 0.074), 0-10 m (p = 0.125), and 0-5 m (p = 0.294) (table 9).

For the NH group, the strong group was significantly faster at 20-30 m (p = 0.013), 20-40 m (p = 0.029), 0-30 m (p = 0.043), 0-40 m (p = 0.045), 10-30 m (p = 0.046), 5-30 m (p = 0.048), and 5-40 m (p = 0.050). The strong group was also faster on 30-40 m (p =0.058), 0-10 m (p =

0.060), COD (p = 0.065), 0-20 m (p = 0.079), 5-10 m (p = 0.089), 0-5 m (p = 0.104), 5-20 m (p = 0.111), and 10-20 m (p = 0.161) (see table 10).

Table 9 Sprint times for Strong vs. weak in HBS group

Strong vs. Weak (HBS)				
Sprint Distance (m)	**Strong Mean (s) (n=5)**	**Weak Mean (s) (n=3)**	**Difference (s)**	**P value**
20-30*	1.19	1.37	0.18	0.028
5-30*	3.24	3.65	0.41	0.029
5-40*	4.45	5.03	0.58	0.030
20-40*	2.40	2.74	0.34	0.032
5-20*	2.05	2.29	0.24	0.032
10-30*	2.47	2.82	0.35	0.035
0-40*	5.43	6.1	0.67	0.047
30-40*	1.21	1.37	0.16	0.047
10-20*	1.30	1.41	0.11	0.048
0-30	4.22	4.73	0.51	0.053
5-10	0.76	0.83	0.07	0.065
COD	9.06	9.51	0.45	0.074
0-20	3.03	3.36	0.33	0.074
0-10	1.74	1.91	0.17	0.125
0-5	0.98	1.08	0.10	0.294

Table 10 Sprint times for Strong vs. weak in NH group

Strong vs. Weak (NH)				
Sprint Distance (m)	**Strong Mean (s) (n=5)**	**Weak Mean (s) (n=4)**	**Difference (s)**	**P value**
20-30*	1.21	1.34	0.13	0.013
20-40*	2.42	2.66	0.24	0.029
0-30*	4.26	4.55	0.29	0.043
0-40*	5.47	5.90	0.43	0.045
10-30*	2.53	2.71	0.18	0.046
5-30*	3.29	3.52	0.23	0.048
5-40*	4.50	4.86	0.36	0.050
30-40	1.21	1.34	0.13	0.058
0-10	1.73	1.85	0.12	0.060
COD	9.00	9.33	0.33	0.065
0-20	3.05	3.23	0.18	0.079
5-10	0.76	0.81	0.05	0.089
0-5	0.97	1.03	0.07	0.104
5-20	2.08	2.2	0.12	0.111
10-20	1.32	1.39	0.07	0.161

* significance < 0.05; COD, change of direction; HBS, half-back squat; m, meter; n, number of participants; NH, Nordic hamstring; s, seconds.

DISCUSSION

This study aimed to investigate and compare the correlations between HBS 1RM and the different sprint distances measured, and the correlation between NH peak force (PF) and the different sprint distances. We also aimed to study the effect of the training program on strength (1RM for HBS and PF for NH), with extra focus on our NH training method as this has not been conducted in research before. The main findings in this study were that both HBS 1RM ($kg·bw^{-0.67}$) and NH PF ($N·bw^{-0.67}$) showed better correlations with sprint time on distances after 10 m, and that the HBS 1RM ($kg·bw^{-0.67}$) correlated better than NH PF ($N·bw^{-0.67}$) with sprint time on all distances and COD sprint time. In addition, both the HBS and NH groups improved strength significantly from the pre-test to the last training session.

The effect of HBS on sprint performance

Contrary to our hypothesis, HBS 1RM ($kg·bw^{-0.67}$) correlated strongly and significantly with all sprint distances and split times, except 0-5 m which showed a moderate correlation ($r = 0.69$, $p = 0.060$). Further, the analysis shows that the differences in HBS 1RM ($kg·bw^{-0.67}$) can explain 87% of the variation in sprint performance on 10-30 and 5-30 m sprint ($r^2 = 0.87$, $p < 0.001$), but only 47% and 59% of the variation in sprint performance on 0-5 m ($r^2 = 0.47$, $p = 0.060$) and 0-10 m ($r^2 = 0.59$, $p = 0.026$), respectively. Overall, the correlations suggest that a greater HBS 1RM ($kg·bw^{-0.67}$) will transfer to faster sprint times, especially on distances after the first 10 m. This is supported by the analysis of sprint time differences between strong and weak players in our study. The strong players were significantly faster than the weak group on the distances 10-20 m, 30-40 m, 0-40 m, 10-30 m, 5-20 m, 20-40 m, 5-40 m, 5-30 m, and 20-30 m ($p < 0.05$). The distances where it was found no significant difference were 0-5 m, 0-10 m, 0-20 m, 5-10 m, and 0-30 m.

Helgerud et al., (2011) found a moderate and significant correlation between HBS 1RM ($kg·bw^{-0.67}$) and 10 m sprint performance in professional soccer players ($r = -0.51$, $p < 0.05$). Further, McBride et al. (2009) studied the correlation between back squat 1RM (performed to a 70° knee joint angle) and sprint performance in male student football players and found similar trends as in our study. Both 40-yard and 10-yard sprint performance correlated significantly with back squat 1RM relative to body mass ($r = -0.61$, $p = 0.010$; $r = -0.54$, $p = 0.024$, respectively), whereas 5-yard sprint performance and HBS 1RM correlation was nonsignificant ($r = -0.45$, $p = 0.069$). Moreover, Comfort et al., (2014) also showed that HBS 1RM relative to body mass correlated higher with 20 m ($r = - 0.67$, $p < 0.001$) compared to 5 m ($r = -0.52$, $p = 0.002$) sprint times in well-trained youth soccer players. However, both McBride et al., (2009) and Comfort et al. (2014) expressed the participants' HBS 1RM as relative to body mass. This will affect the correlations and it is also difficult to compare our results with these studies as we scaled the HBS 1RM differently ($kg \cdot bw^{-0.67}$). Nevertheless, these results are surprising as we expected the HBS 1RM to correlate strongly with the acceleration phase, which is supported by EMG analysis showing that quadriceps and gluteals are crucial in that phase (Morin et al., 2015). However, the fail to find a strong correlation between 0-5 m sprint and HBS 1RM in our study and previous research may have a logical explanation. Looking at the three trials of each participant in our study, there were large intra-individual differences in the sprint time on 0-5 m (ranging from 0.01-0.09 s). This may indicate that achieving maximum performance on 5 m from a standing start is highly difficult for inexperienced sprinters. Nevertheless, Wisløff et al., (2004) found a strong and significant correlation between 0-10 m sprint performance and HBS 1RM ($kg \cdot bw^{-0.67}$) ($r = -0.94$, $p < 0.001$) in male senior elite soccer players, whereas the correlation between 0-30 m and HBS 1RM ($kg \cdot bw^{-0.67}$) was lower ($r = -0.71$, $p < 0.01$). This is the opposite trend of that observed in our study as we observed a higher correlation between HBS 1RM ($kg \cdot bw^{-0.67}$) and 0-30 m ($r = -0.89$, $p = 0.003$) compared to the correlation between 0-10 m ($r = -0.77$, $p = 0.026$). However, the different age and level of play may account for some of the differences in correlation between Wisløff et al. (2004) and our study. In summary, although correlation studies are conflicting whether HBS 1RM correlates better with the first 10 m or after 10 m, our correlations suggest that improving HBS 1RM ($kg \cdot bw^{-0.67}$) will lead to greater improvements on sprint performance especially after the first 10 m, which is supported by (McBride et al. 2009) and Comfort et al. (2014).

The effect of NH on sprint performance

In line with our hypothesis, NH PF ($N \cdot bw^{-0.67}$) correlated significantly and strongly with all sprint distances, except 0-10 m, 5-10 m, and 0-5 m, whereas the strongest correlations were found at 20-40 m, 20-30 m, 30-40 m, and 10-40 m. Our analysis show that the differences in NH PF ($N \cdot bw^{-0.67}$) can explain 74% of the variation in sprint performance on 20-40 m ($r^2 = 0.74$), but only 25% of the variation in sprint performance on 0-5 m ($r^2 = 0.25$). Further, the analysis of the strong vs. weak players in the NH exercise supports our correlations. The strong group was significantly faster at the distances; 20-30 m, 20-40 m, 0-30 m, 0-40 m, 10-30 m, 5-30 m, and 5-40 m ($p < 0.05$). This indicates that the hamstring musculature is more important at higher sprinting speeds, which also is supported by biomechanical principles and

EMG-analysis of sprinting. These analysis show that the hamstrings are crucial at higher sprinting speeds, as being able to suppress the braking forces in the early stance phase is key for achieving greater acceleration and maintaining maximum speed (Nagahara et al., 2018). In addition, the hamstrings are increasingly activated with increased speed (Albertus-Kajee et al., 2011; Bartlett et al., 2014; Higashihara et al., 2010; Kuitunen et al., 2002; Kyrölainen et al., 2005; Mastalerz et al., 2012; Nummela et al., 1994). However, regarding the weak correlations between NH PF ($N \cdot bw^{-0.67}$) and sprint distances involving the first 5 m of the sprint, the same potential reasons as suggested for HBS 1RM ($kg \cdot bw^{-0.67}$) and 0-5 m sprint performance are proposed. Thus, the NH exercise may be more important from 0-5 m than the correlations suggest. Further, to the authors knowledge, only one previous study has investigated the correlation between NH strength and sprint performance. Marcovic et al., (2020) found a moderate significant correlation between NH strength and 0-20 m sprint performance ($r = -0.52$; $p < 0.01$). In comparison we found a strong and significant correlation between NH PF ($N \cdot bw^{-0.67}$) and 0-20 m sprint performance ($r = -0.70$, $p = 0.035$). However, Marcovic et al. (2020) did not scale for body mass. This will overestimate the strength of the larger and heavier players and most likely affect the correlations. Overall, the results support our hypothesis that the hamstrings are more important after the first 10 m, but especially after 20 m.

Comparative effect of the HBS and NH on sprint performance

Partially in line with our hypothesis, HBS 1RM ($kg \cdot bw^{-0.67}$) correlated better with all sprint distances compared to NH PF ($N \cdot bw^{-0.67}$). For example, our analysis showed that the differences in HBS 1RM ($kg \cdot bw^{-0.67}$) can explain 47% of the variation in sprint performance on 0-5 m ($r^2 = 0.47$, $p = 0.060$). In comparison, the differences in NH PF ($N \cdot bw^{-0.67}$) can only explain 25% of the observed differences in sprint performance on 0-5 m ($r^2 = 0.25$, $p = 0.176$). This is in line with our hypothesis which stated that HBS should correlate better with the acceleration phase. This is also supported by EMG-analysis which shows that the quadriceps and gluteals are more activated then the biceps femoris in the acceleration phase (Morin et al., 2015). On the other hand, not in line with our hypothesis, the correlation between HBS 1RM ($kg \cdot bw^{-0.67}$) and sprint performance on 20-40 m ($r = -0.91$, $p = 0.002$) was higher compared to the correlation between NH PF ($N \cdot bw^{-0.67}$) and 20-40 m sprint performance ($r = -0.86$, $p = 0.003$). However, the correlation between HBS 1RM ($kg \cdot bw^{-0.67}$) and 0-20 m was 18.6% higher than the correlation between NH PF ($N \cdot bw^{-0.67}$) and the corresponding distance, whereas the HBS 1RM only correlated 5.5% higher than NH PF ($N \cdot bw^{-0.67}$) with 20-40 m sprint time. This is also the general trend; there is a smaller difference between the correlations for HBS 1RM (kg·bw$^{-0.67}$) and NH PF (N·bw$^{-0.67}$) at the sprint distances after 5 m, but especially after 20 m (see differences in table 2). This may support our suggestion that the HBS exercise is more beneficial for acceleration (0-10 m), whereas the NH exercise is increasingly important with higher speeds (although not more important than the HBS).

These findings are not in line with previous interventional studies. When summarizing the effect of HBS and NH on sprint performance from existing research, it is revealed that the NH exercise (Ishøi et al. 2018; Krommes et al. 2007; Siddle et al., 2009; Suarrez-Arrones et al. 2019) provided almost double magnitude changes on 10-m sprint performance (4.54% vs. 2.45%), and almost three times greater improvement on 20-m sprint performance (4.5% vs. 1.6%), compared to HBS (Chelly et al., 2009; Helgerud et al. 2011; Rønnestad et al. 2008; Rønnestad et al. 2011). The other distances were not possible to compare due to only some distances being measured. These results are somehow surprising as the HBS targets several muscle groups both concentrically and eccentrically, while the NH almost exclusively activates the hamstrings eccentrically. In addition, based on EMG-analysis of sprinting, the quadriceps and gluteals are activated to a larger degree than the hamstring in the acceleration phase (Morin et al., 2015), and therefore it would have been logical that the HBS should have led to larger improvements. However, it must be noted that three out of four analyzed HBS studies were performed on elite (Helgerud et al. 2011) or professional (Rønnestad et al. 2008, Rønnestad et al. 2011) players, while the studies conducting the NH were performed on amateur (Ishøi et al. 2018; Siddle et al. 2019) and semi-professional (Krommes et al. 2017) senior players, and professional youth players (Suarez-Aronnes et al. 2019). Therefore, the participants in the NH studies may have had a larger unreleased potential for improving sprint performance due to a poorer level of play and/or training status. Importantly, all the above studies have several flaws in their research design, which is outlined earlier in this study, making it difficult to make any conclusion.

Nevertheless, the findings in the above-mentioned interventional studies, which demonstrates that NH leads to greater improvements in sprint performance compared to HBS MST, may also have a logical explanation. Sprinting produces stretch-shortening cycle (SSC) actions which are a sequential combination of eccentric and concentric muscle actions (Komi, 1986). Movements that involve the SSC leads to greater concentric force outputs if there is a rapid and efficient storage and transfer of elastic energy from the eccentric to the concentric phases

(Bosco et al. 1982a,b; Cormie et al., 2010; Cavagna et al., 1968). Therefore, it is paramount that the transition from eccentric to concentric phases are of short duration (McCarthy et al., 2012), which requires sufficient hamstring strength to absorb the eccentric energy and quickly convert it to a concentric action. Further, reaction forces from sprinting can be 4-6 times the individual's body mass (Mero et al., 1992; Cappa & Behm, 2011), thus, an athlete lacking eccentric strength must absorb the eccentric forces experienced with sprinting over a longer duration. This will negate the advantages of the SSC (Miyaguchi & Demura, 2008), and possibly lead to poorer sprint performance. A poor eccentric hamstring to concentric quadriceps (H:Q) ratio is a muscular imbalance which is evident across all athletes and sports (Aagaard et al., 1998), and research also shows that a poor H:Q make players more vulnerable for hamstring injuries (Coratella, et al., 2015; Delextrat et al., 2010; Fousekis et al., 2011; Liu et al., 2012). Based on the above, it is likely that sprint performance in soccer players is limited by poor hamstring strength and a low H:Q ratio, which may be reflected by the large increases in sprint performance seen in the mentioned interventional NH studies. Thus, although the correlations between sprint performance and NH PF ($N \cdot bw^{-0.67}$) is lower than the correlation between HBS 1RM ($kg \cdot bw^{-0.67}$) and sprint performance in our study, it may be evident that the NH exercise can provide greater improvements in sprint performance since soccer players seem to possess weak hamstrings and/or a low H:Q ratio. Based on this, it is also fair to suggest that the effect of HBS MST on sprint performance can be blunted if the players possess a low H:Q ratio. Therefore, since our correlation analysis results and the existing interventional studies on the effect of HBS and NH are conflicting, the effect of the HBS and NH on sprint performance should be investigated and compared in the same study, as we intended to do. In addition, looking at the association between H:Q ratio and sprint performance should also be of interest.

The effect of HBS and NH on COD-sprinting and jump height

In line with our hypothesis, both HBS 1RM ($kg \cdot bw^{-0.67}$) and NH PF ($N \cdot bw^{-0.67}$) correlated significantly and strongly with COD sprint performance. This was expected as COD sprinting requires eccentrically work by the hamstring musculature when breaking (Brughelli, et al., 2008; Chaouachi et al., 2012; Jones et al., 2009), and concentrically work by the quadriceps when accelerating (Coratella et al., 2018). However, The HBS 1RM ($kg \cdot bw^{-0.67}$) correlated 13.6% higher with COD sprint performance ($r = -0.88$, $p = 0.004$), than NH PF ($N \cdot bw^{-0.67}$) did ($r = -0.76$, $p = 0.018$). In comparison, Chaabane et al. (2018) reviewed the correlation between eccentric hamstring strength and COD sprint performance in athletic population. They could reveal that the literature is raging from a moderate to strong correlation ($r = -0.45–0.89$). Further, Wisløff et al., (2004) found a significant moderate correlation between HBS 1RM ($kg \cdot bw^{-0.67}$) and a shuttle run test ($r = -0.68$, $p < 0.02$) in elite senior male soccer players. However, they performed 180° turns, whereas we used 90° turns. This may be the reason for the different findings. Nevertheless, no interventional studies have investigated the effect of HBS MST alone on COD sprint performance, whereas Siddle et al. (2019) is the only study to test the effect of NH on COD sprint performance. They showed that 10 weeks of NH training improved COD sprint performance by 2.7% (-0.12 s) in amateur soccer and rugby players. Due to the limited research, future studies should investigate and compare the effect of HBS and NH on COD sprint performance in soccer players. Importantly, the fact that research use different COD sprint tests is a limitation when comparing studies related to COD sprinting. Thus, it is important to find a standardized COD sprint test. It is suggested that future research within soccer should consider adopting our COD sprint test because it is based on frequent COD angles performed in soccer games.

HBS 1RM ($kg \cdot bw^{-0.67}$) correlated significantly and strongly with CMJ ($r = 0.86$, $p = 0.007$), 39.5% higher than NH PF ($N \cdot bw^{-0.67}$) and CMJ ($r = 0.52$, $p = 0.153$). Previous research has also reported a strong correlation between HBS and jumping performance. For example, Wisløff et al. (2004) found a strong correlation between HBS 1RM ($kg \cdot bw^{-0.67}$) and jump height ($r = 0.78$, $p < 0.002$). Further, interventional studies have documented an improvement in CMJ ranging from 1.6 - 3.0 cm or 4.6 - 7.4% after HBS MST (Chelly et al., 2009; Helgerud et al., 2011; Rønnestad et al., 2008; Rønnestad et al., 2011). To the authors knowledge, no studies have looked at the correlation between NH PF and CMJ height. However, Krommes et al., (2017) improved CMJ in youth soccer players by 1.15 cm or 2.63% in elite male soccer players after 10 weeks with NH training. Similarly, Suarez-Arrones et al., (2019) improved CMJ by 1.8cm or 4.6% CMJ in a similar intervention. Based on the correlations in our study and the existing research, the HBS exercise should be superior to NH exercise when it comes to improving CMJ performance.

Correlation between COD sprint, CMJ height, and straight-line sprint performance

The correlation between COD sprint time and straight-line sprint performance was strong for all distances ($r = 0.77-0.93$, $p < 0.001$). The COD sprint test in our study was designed to replicate the most used change in direction used in soccer, but at the same time to challenge the higher angles that regularly occur (up to 90°) (Bloomfield et al., 2007). The trend was that faster players on straight-line sprinting were also faster at the COD-sprint, but the correlation indicates that the speed around 20-30 m correlates strongest with COD performances. Previous research has not found a correlation between a shuttle-run test and sprint performance on 0-10 m and 0-30 m (Wisløff et al., 2004). However, the test in Wisløff et al., (2004) required the players to sprint 10 m forward, around a cone and back to the finish-start line. The kinetic energy of an object is directly proportional to the square of its speed. Thus, for a twofold increase in speed, the kinetic energy will increase by four, and for a fourfold increase in speed, the kinetic energy will increase by 16. This means that faster players must counteract greater kinetic energy when changing direction, especially if the players are heavier as well. Thus, in a 180° turn, the players have to counteract all the kinetic energy, and a faster player will have to counteract higher levels of kinetic energy compared to the slower players. Although faster players often are stronger, the extra strength needed to counteract the kinetic energy in a 180° turn may be greater than what is evident. Therefore, slower players may have a benefit *in the turn*, and this may be the reason for Wisløff et al. (2004) not finding any correlation between straight-line sprint performance and the shuttle-run test. On the other hand, when performing a 90°-turn, as in our study, the participant does not have to counteract all the kinetic energy and forward movement, but they can maintain some of the speed and momentum in the turn. Therefore, in our COD sprint test faster players will most likely benefit more of the high speed leading to stronger correlations with straight-line sprint performance.

The CMJ correlated strongest with COD sprint performance ($r = -0.85$, $p < 0.001$). The correlation between CMJ and sprint performance was also strong at the distances 20-30 m ($r = -0.73$, $p = 0.001$), 10-30 m ($r = -0.71$, $p = 0.001$), 0-30 m ($r = - 0.71$, $p = 0.001$), 5-10 m ($r = -0.70$, $p = 0.002$). Previous research showing a strong correlation between CMJ and sprint performance is well documented. In a review by Haugen et al. (2013), there was a strong correlation between CMJ and 0-20 velocity ($r = 0.63$, $p < 0.001$, $n = 633$). This indicate that increasing CMJ performance will lead to improvement in COD sprint, and straight-line sprint performance. However, based on the correlations, CMJ seem to transfer more to improved COD sprint performance which is natural as both CMJ and COD sprinting requires eccentrically and concentrically work in the execution of the jump and turn. Further, the strong correlation between vertical jump performance and sprint times is expected as both are derivates of maximal strength (Wisløff et al., 2004). As HBS 1RM ($kg \cdot bw^{-0.67}$) correlates better with CMJ than NH PF ($N{\cdot}bw^{-0.67}$), and CMJ correlates strongly with COD sprinting, HBS may be a better exercise to both improve CMJ and COD sprint performance.

Changes in strength

HBS

The HBS group improved 1RM by 56% ($p < 0.001$) from the pre-test to the last training session (see methods for calculations of 1RM), showing that the HBS MST leads to significant increases in 1RM in youth professional soccer players. Based on Newton's second law of motion, which states that for a given mass acceleration is directly proportional to force magnitude, a substantial increase in strength per kg body weight would be expected to increase acceleration (Helgerud et al., 2011). Previous research has reported similar gains in 1RM after HBS MST. Similar to us, Helgerud et al., (2011) significantly improved strength by 52% ($p < 0.001$) after 2 weekly HBS MST sessions for 8 weeks in elite senior male soccer players. On the other hand, Rønnestad et al. (2011) observed a significant increase of 19% ($p < 0.01$) in HBS 1RM after 2 weekly HBS training sessions for 10 weeks in professional soccer players. This is a substantial lower than what observed in our study. However, they started the training period with a load of 10RM, and gradually increased the load to 4RM, resulting in only 3 weeks of MST. This may explain the lower increase in 1RM compared to our study. Moreover, Rønnestad et al. (2008) improved HBS 1RM by 21% ($p < 0.01$) after 8 weeks of 2 weekly HBS MST sessions in professional male soccer players. Further, Chelly et al. (2009) conducted an 8-week HBS MST regimen with two sessions per week in youth soccer players and significantly improved HBS 1RM by 26% ($p < 0.05$). They performed four sets per session (1st set; 7 repetitions, 70% of 1RM, 2nd set; 4 repetitions, 80% of 1RM, 3rd set; 3 repetitions, 85% of 1RM, and 4th set; 2 repetitions, 90% of 1RM). However, Chelly et al. (2009) used the same weight for 4 weeks, before reassessing the 1RM and updating the training weight. In comparison, we gradually increased the weight by 5 kg every time the participant where able to complete 4 repetitions with optimal technique. Because the participants did not have any previous experience with strength training large increases in training weight is expected the first weeks of training. This was also evident in our study. Therefore, it is fair to suggest that Chelly et al. (2009) missed out on improvements the first 4 weeks of the MST regimen. Overall, it is a clear consensus that HBS MST significantly improves HBS 1RM.

NH

To the authors knowledge, we were the first to train the NH exercise with principles of MST implemented. The NH group improved strength significantly from the pre-test to the last training session (39%, $p < 0.001$) (see methods for calculations of PF). In comparison, studies that have investigated the effect of NH exercise on sprint performance have increased the number of repetitions and sets when the player is strong enough to perform 4 repetitions, instead of adding weight and training with the maximal strength principle. In example, Suarez-Arrones et al., (2019) completed a 17-week NH exercise protocol (24 sessions in total) on junior professional soccer players. They increased the NH PF by 13.6% in the group that had no experience with the NH exercise. The group with previous experience with the NH exercise only increased their NH PF by 1.8%. This underlines the issue of not adding weight. When the participants are strong enough to perform the whole NH exercise movement, strength improvements will stop as they only increase repetitions and sets. Further, Ishøi et al., (2018) improved NH PF by 16.1% after 10 weeks (27 sessions) of NH training in amateur male soccer players. Interestingly, we observed a mean post NH PF of 381.1 N. In comparison, professional senior soccer players with previous hamstring training history had a mean NH PF of 411 N (Bucheit et al., 2016), which is only slightly greater than what observed in our study. However, these subjects were on average 16.2 kg heavier than our subjects, which will provide larger values. When using the same scaling method as done in our study ($N \cdot bw^{-0.67}$), our subjects possess higher NH PF compared to the professional senior soccer players in Bucheit et al. (2016) (23.6 N vs. 21.9 N). Thus, youth soccer players in our study only needed 18 sessions with our NH training method to exceed the NH PF in senior professional soccer players with previous NH training history. This also supports our earlier suggestion that soccer players may attain greater improvements in sprint performance by training NH compared to HBS because they possess weak hamstring and a most likely a low H:Q ratio.

In summary, these results show that our NH training method of adding 2.5 kg when the players are able to complete the whole movement for four repetitions and two sets lead to greater gains in NH PF compared to NH training with only body weight. In addition, our results and the existing research indicate that most players lack eccentric hamstring strength, although they have trained the NH exercise previously. This is most likely because players do not train the NH exercise with the MST principles implemented, whereas MST is used to train other muscle groups. Thus, this underpins that our NH training method is a superior method to improve NH strength. It is also likely that this training method will lead to superior gains in sprint performance as there is a strong correlation between NH PF and sprint performance as shown in our study. No injuries or discomfort was reported during the intervention, so there is no reason to not train the NH exercise the same way we normally train all other muscle groups that is important for sprinting.

When is maximal sprint speed reached? – Implications for testing practice

The results in the present study show that players most likely reach their maximum speed after 20 m. This is reflected by the 20-30 m split time (1.26 s, 28.57 km/h) being faster than the 30-40 m split time (1.27 s, 28.35 km/h). However, it should be noted that these sprint times are very similar and when looking at each individual player some are faster from 20-30 m while others are faster from 30-40 m. This indicate that it is important to measure split times up to 40 m if the goal is to measure the players' maximum speed, because some players first will reach top speed after 30 m. Supporting this, although 50% of all sprints in soccer are less than 10 m, sprints in soccer often reach up to 30 m (Stølen et al., 2005). Importantly, a 10 m sprint in a game will reach a higher speed than a sprint test from a stationary start because in games players almost exclusively starts the sprint from either a walking or jogging condition. In example, it is reported that high school and college soccer players conduct 85% of their sprints from a non-stationary condition (Balsom, 1994). Further, Duthie et al., (2006) documented that rugby players reached top speed 1.5-2 s faster when the sprint was started from a jogging or striding condition. This equals the time spent from 0-10 m in our study (1.81 s). Thus, when testing sprint in research this should be accounted for by adding 10 m extra in sprint distance, because the in-game speed at 20 m (if starting from a jogging or striding condition) will most likely reflect 30 m speed in a sprint test from stationary start.

It can also be questioned how important the first 5 m in a sprint test is when starting from a stationary condition as this does not reflect what is happening in games where players start sprinting from a non-stationary condition. If the improvements in sprint performance after a given training protocol is almost exclusively occurring within the first 5-meter, will it be beneficial for soccer players? In example, Helgerud et al. (2011) got a 0.06 s improvement in 10 m performance (from a stationary start) after 8 weeks with HBS MST. However, the participants got 0.01 s slower from 10-20 m. Given that players normally start sprinting from a walking, jogging or striding condition, which will result in reaching top speed 1.5-2 s earlier, the improvement in Helgerud et al. (2011) may not be as beneficial as it seems. Further, both HBS 1RM and NH PF showed weaker correlations with 0-5 m sprint, compared to greater sprint distances, in our study. This was similar in other research as well (Comfort et al., 2014; McBride et al. 2009). However, a common practice today is to place the starting line 30 cm behind the first photocell. Thus, this will not reflect a soccer-specific sprint which is normally conducted from a non-stationary condition. Therefore, to better replicate the nature of a soccer-specific sprint, the first photocells should be placed 1-2 m in front of the starting line when testing sprint performance in soccer players. Further, as correlations between maximal strength and sprint performance are shown to be higher with distances longer than or after 5 m, it is fair to suggest that the correlation between maximal strength and 5 m sprint time may be higher when starting 1-2 m behind the first photocell.

In summary, future research should test several split times up to 40 m if the goal is to measure maximum speed as some players seem to reach top speed around or after 30-40 m. In addition, the starting line should be 1-2 m behind the first photocell to better reflect a soccer specific sprint which normally is performed from a non-stationary condition. This will be important for future studies aiming to investigate the correlation between maximal strength and sprint performance, and for general sprint testing of soccer players.

CONCLUSION

In conclusion, the correlation between HBS 1RM ($kg \cdot bw^{-0.67}$) and straight-sprint performance was better at sprint distances after 10 m, indicating that being stronger in the HBS will transfer to faster sprint times, especially on distances after the first 10 m. On the other hand, the strongest correlation between NH PF ($N \cdot bw^{-0.67}$) and straight-sprint performance was found at 20-40 m, 20-30 m, 30-40 m, and 10-40 m, indicating that NH training may be more effective to improve sprint performance after 10 m, and especially from 20-40 m. Both HBS 1RM ($kg \cdot bw^{-0.67}$) and NH PF ($N \cdot bw^{-0.67}$) correlated strongly with COD sprint time, suggesting that increasing strength in both exercises should lead to better COD sprint performance. Further, the correlation between HBS 1RM ($kg \cdot bw^{-0.67}$) and sprint performance was higher than the correlation between NH PF ($N \cdot bw^{-0.67}$) and sprint performance on all sprint distances and the COD sprint test. This may indicate that improving HBS 1RM is more beneficial than improving NH PF for overall sprint performance. Further, the HBS group significantly improved HBS 1RM and the NH group significantly improved NH PF, showing that both training methods were highly effective for improving strength. Importantly, the NH training method employed in our study (with MST principles) resulted in greater gains NH PF compared to the commonly used NH training method (only bodyweight, increasing sets and repetitions). Therefore, it is suggested that soccer players should implement our NH training method to more effectively improve eccentric hamstring strength.

Future perspectives

We aimed to be the first to investigate the comparative effect HBS and NH on sprint performance in soccer players and study the effect on different sprint distances. However, the post-tests were not conducted because Norway went into lockdown due to the COVID-19 outbreak. Although our results found higher correlations between HBS and sprint performance compared to NH and sprint performance, the differences were small at sprint distances after 20 m. In addition, since soccer players seem to lack eccentric hamstring strength and have a low H:Q ratio, there may be evident that the NH exercise may lead to similar or better improvements in sprint performance as the HBS exercise, especially on distances after 20 m. This should be investigated in future research. Further, todays research regarding the effect of HBS and NH on sprint performance have been conducted with poor research design. It is suggested that future studies must include a CG that restrain from any form of strength, jump, and sprint training. In addition, the intervention groups should also avoid any other form for strength, jump and sprint training than the exercise studied. Moreover, sprints in soccer are normally performed from a non-stationary condition. Therefore, future studies should test split distances up to 40 m as many sprints in soccer reach up to 30 m, and when starting a sprint from a jogging or striding condition players can reach top speed up to 10 m earlier. In addition, many players in our study seemed to reach top speed around 30 m from a stationary start. Lastly, it is suggested that future studies should place the first photocell 1-2 m in front of the starting line when testing sprint performance to better reflect soccer-specific sprinting as this normally is performed from a non-stationary condition.

Limitations

Some issues may have affected the results in this study. There was a low number of participants in both groups (HBS = 8, NH = 9) which decreases the statistical power. In addition, the accuracy and reliability of the FitLight system used for testing COD sprint speed is not documented. Further, the analysis of improvements in HBS maximal strength and NH is not 100% correct as the post-test strength was calculated using the 4RM weight in the last training session.

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